Neutrino Production at Spallation Sources

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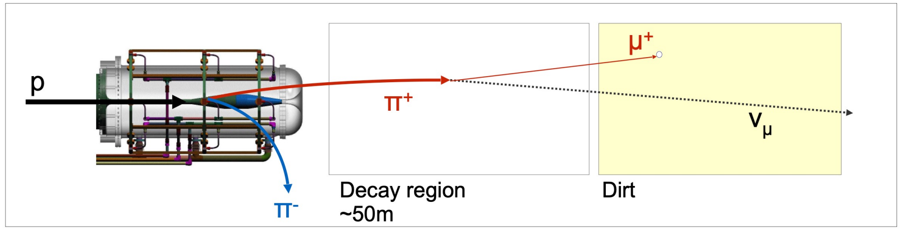
Neutrino Production at Accelerators

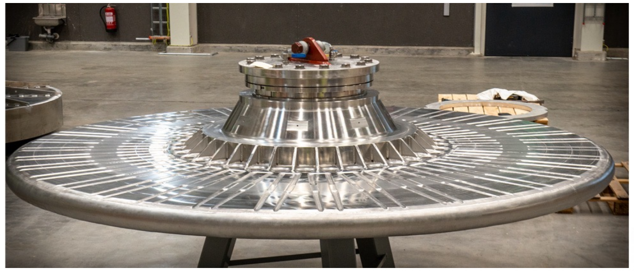
Decay In Flight (DIF)

To generate neutrino beams



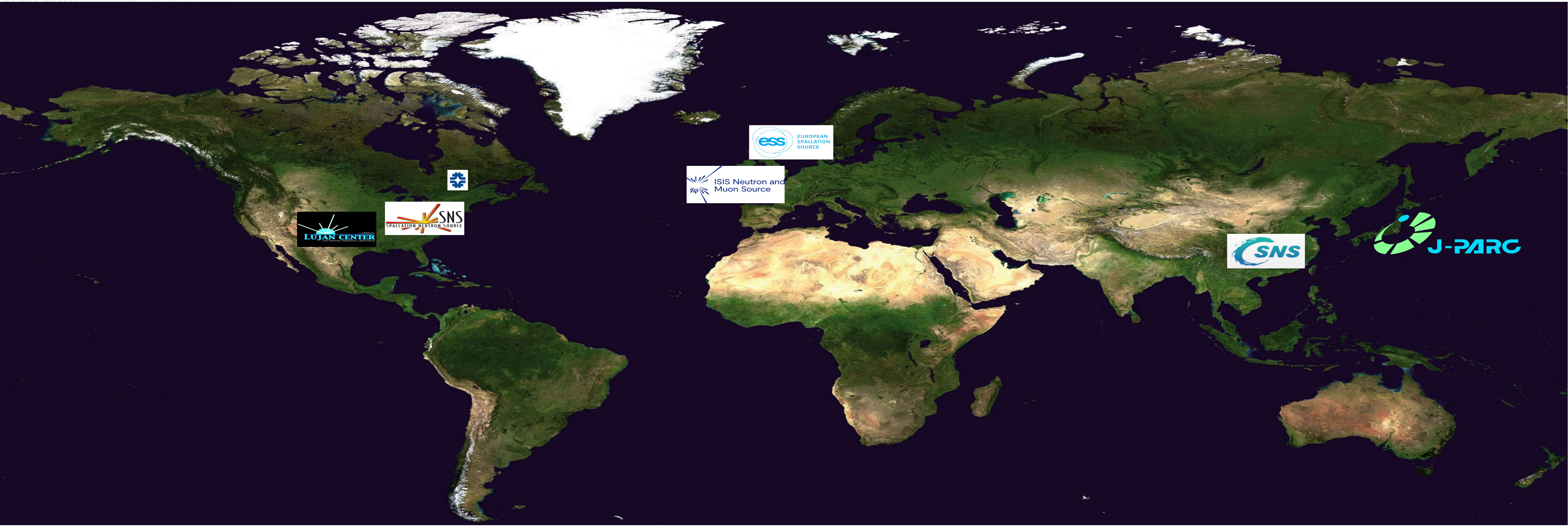
Decay At Rest (DAR)

To generate neutrino flux



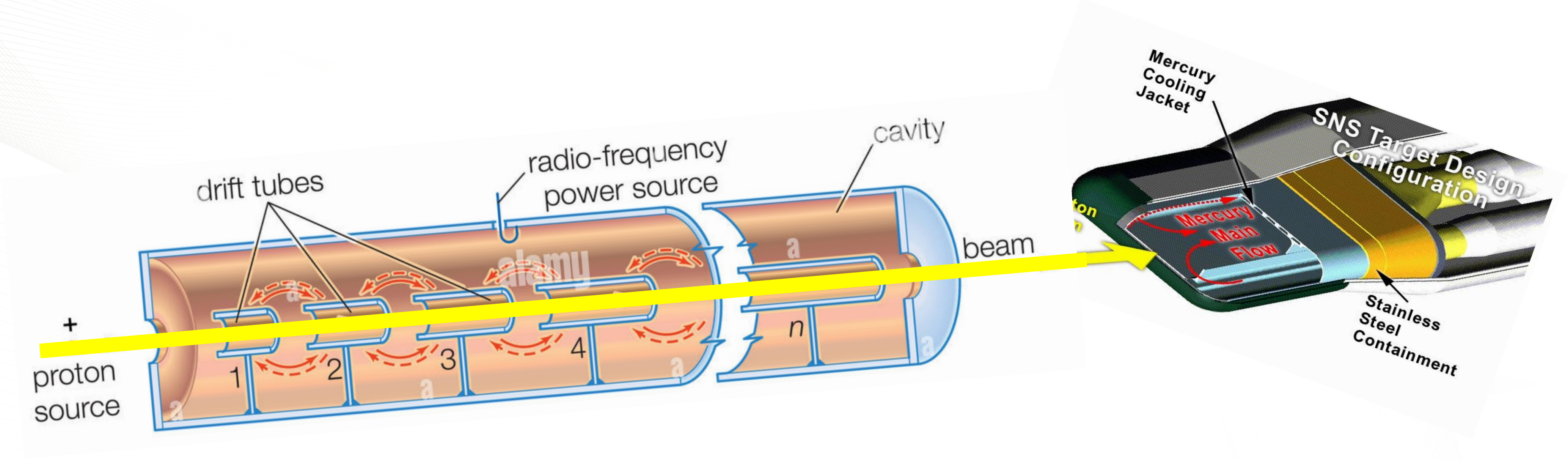
	DIF	DAR
Target Material	Light	Heavy
Energy of Interactions	Around initial proton energy	From the initial proton energy till the pion production threshold
Pion Direction	Forward	$\int \theta$
Pion Momentum	~GeV/c range	$\int p$
Neutrino Flavors	$Mostly\ \nu_\mu\ or\ \overline{\nu}_\mu$	$\nu_\mu, \overline{\nu}_\mu, \nu_e$

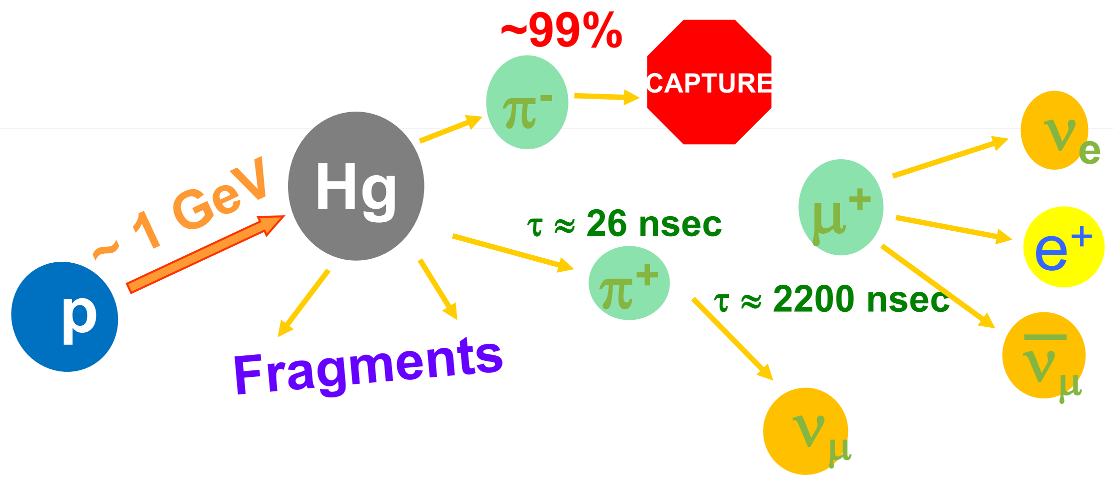
Spallation Facilities



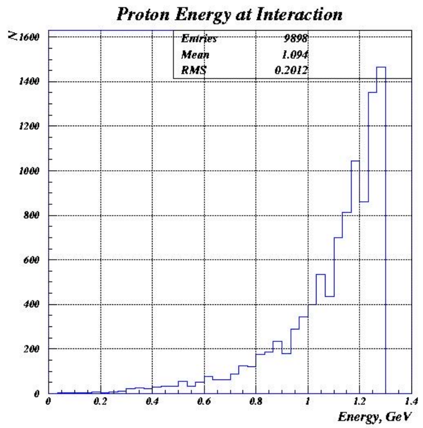
Facility	Proton Energy	Beam Power	Time Structure	Repetition Rate
CSNS, IHEP, China	1.6 GeV	0.16 MW	~500 nsec	25 Hz
ISIS, Rutherford Appleton Lab, UK	0.8 GeV	0.16 MW	2 x 200 nsec	50 Hz
Lujan center, LANL, USA	0.8 GeV	0.8 MW	600 μsec	120 Hz
MLF, J-PARC, Japan	3.0 GeV	1.0 MW	2 x 100 nsec	25 Hz
SNS, ORNL, USA	1.0 GeV	1.7 MW	600 nsec	60 Hz
ESS, Lund, Sweden	2.0 GeV	5.0 MW	3 msec	14 Hz

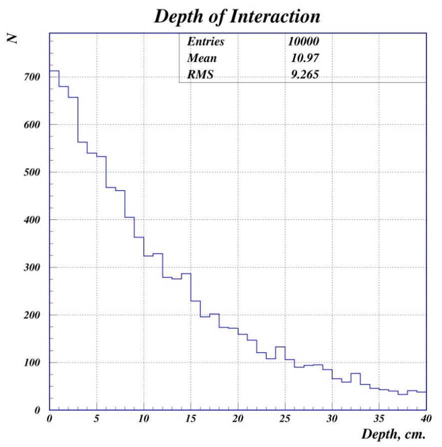
Neutrino Production at a Spallation Source





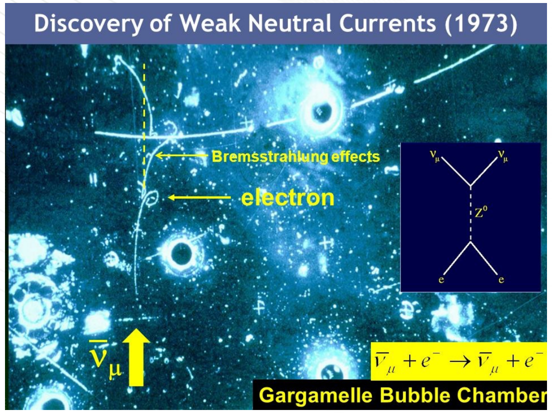
For Initial 1.3 GeV proton on mercury target average interaction energy is 1.1 GeV and average depth of interaction is 11 cm





Why Do We Need to Know Neutrino DAR Rates Accurately?

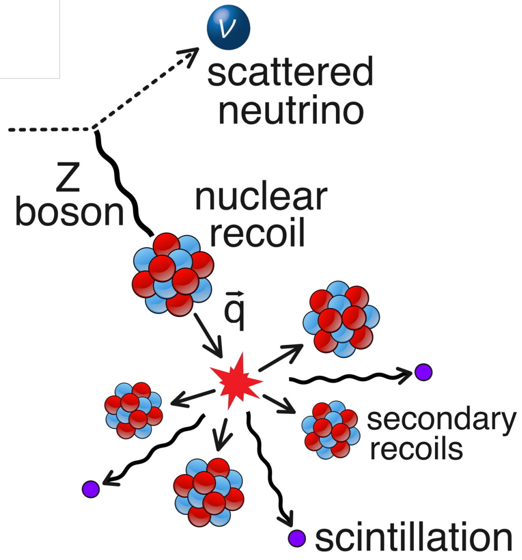
Experimental Discovery of Coherent Elastic Neutrino Nucleus Scattering (CEvNS) in 2017 gave us a new tool to test the Standard Model

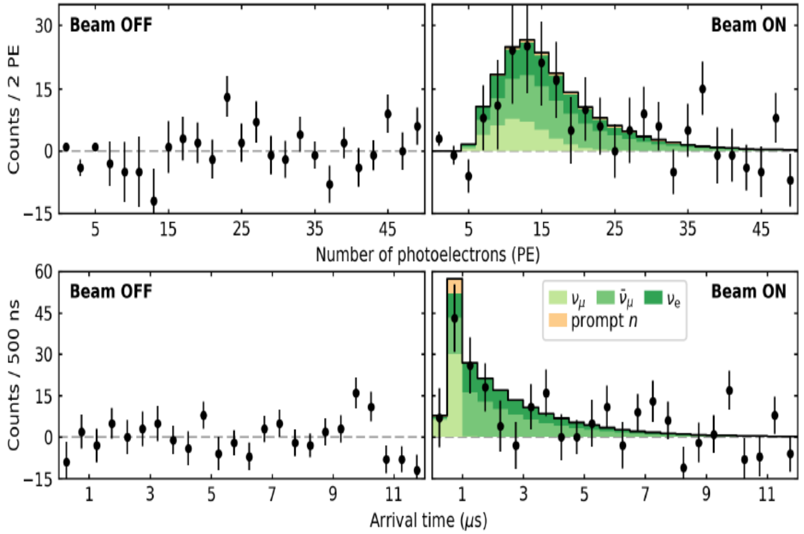


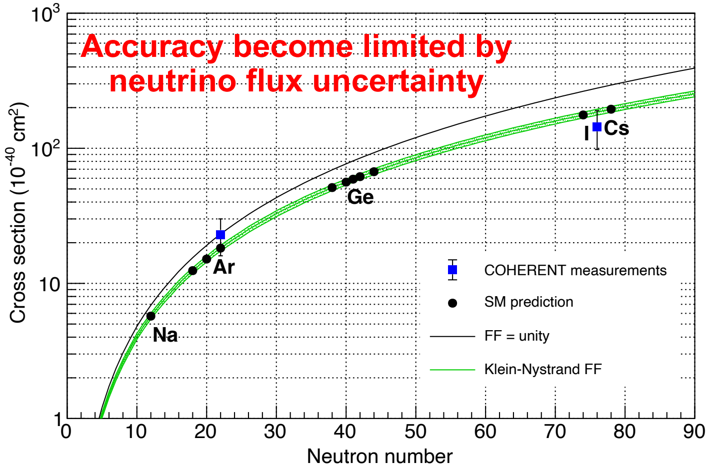
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

D.Z. Freedman PRD 9 (1974)

V.B.Kopeliovich & L.L.Frankfurt JETP Lett. 19 (1974)





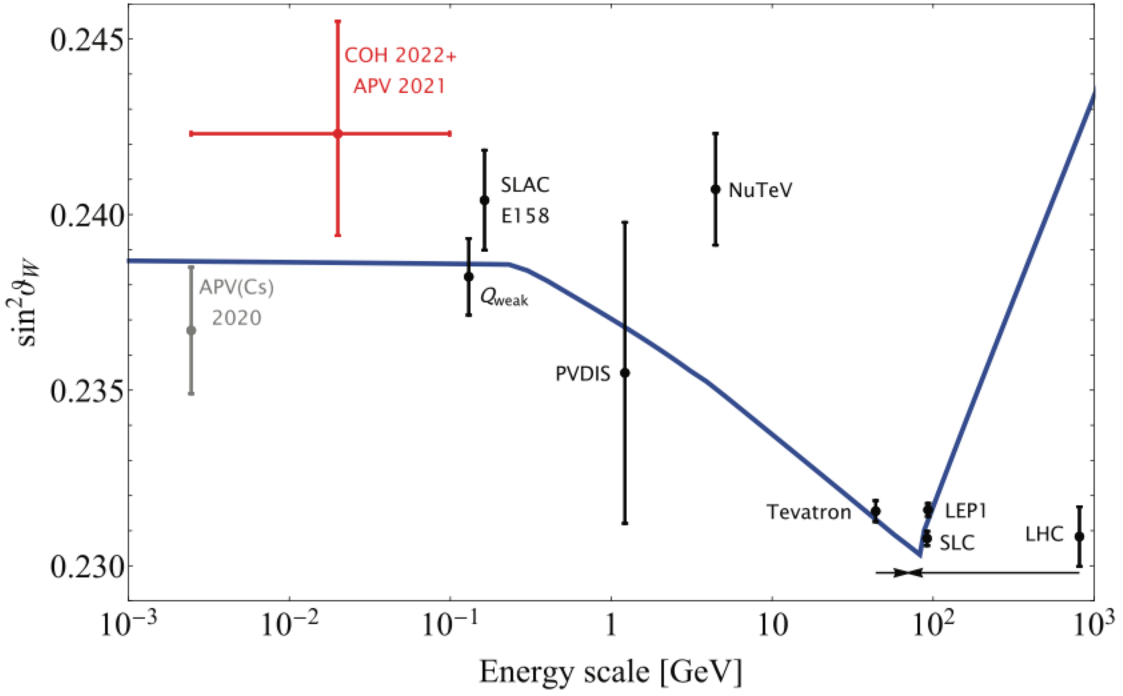


CEvNS is a Probe of Deviation from the SM.

CEvNS is a new way to measure Electro-Weak angle at Low Q

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

Cadeddu, M., F.Dordei, and C.Giunti, Europhysics Letters 143.2 (2—3): 34001



New interaction specific to ν's

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

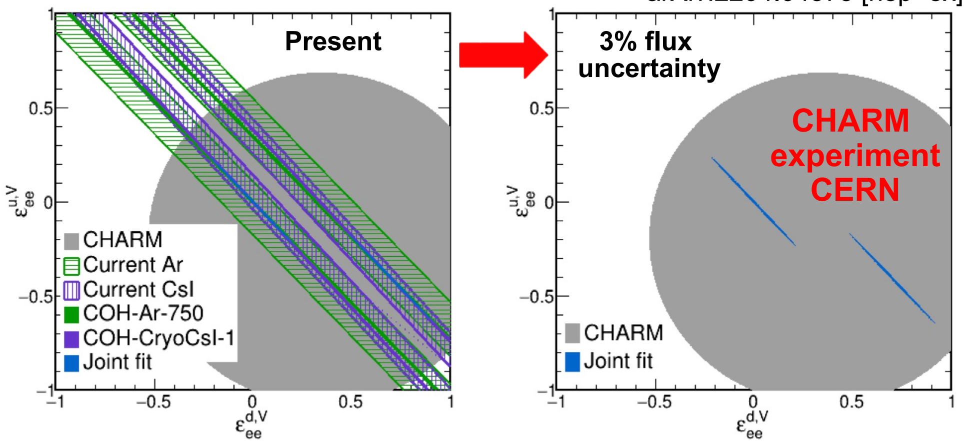
J. High Energy Phys. 03(2003) 011

TABLE I. Constraints on NSI parameters, from Ref. [35].

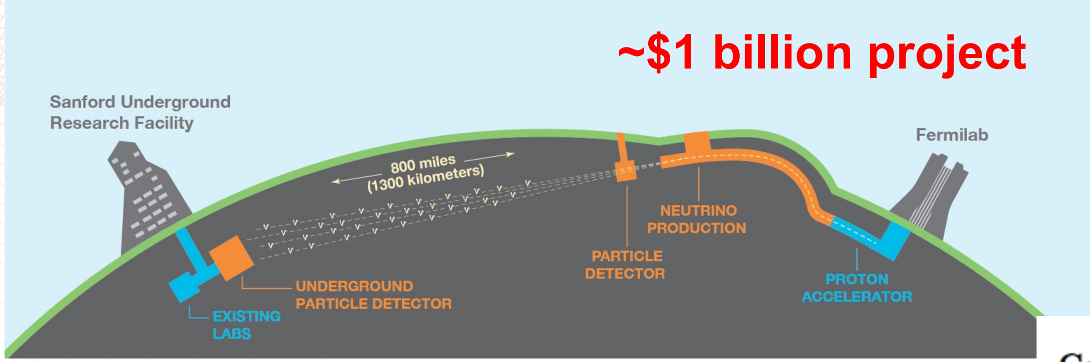
NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Non-Standard ν Interactions
(Supersymmetry, neutrino mass models)

arXiv:2204.04575 [hep=ex]



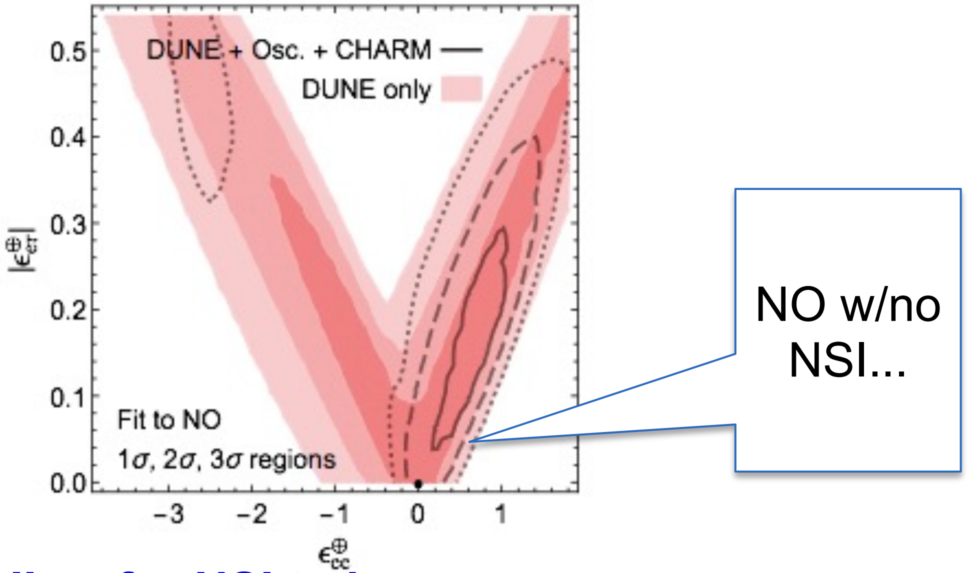
CEvNS are Important as a Probe for NSI.
NSI can create degeneracy for DUNE

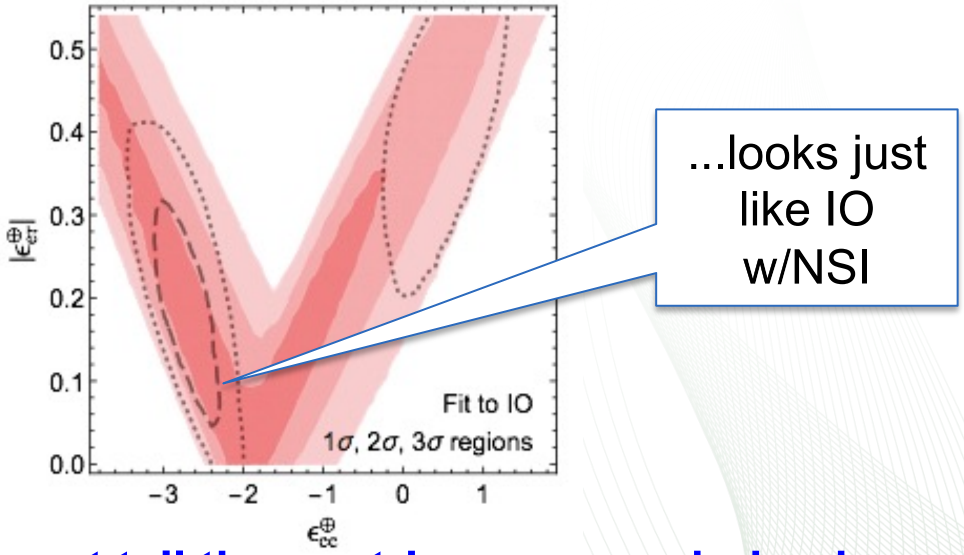


– **measuring the charge-parity (CP) violating phase CP,**
– **determining the neutrino mass ordering (the sign of Δm^2_{12})**
– **precision tests of the three-flavor neutrino oscillation paradigm**

Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2] arXiv:1604.05772v1





If you allow for NSI to have non-zero contribution, degeneracy appears.

We can not tell the neutrino mass ordering in DUNE without constrains on NSI

We Checked Following Nuclear Models for the Pion Production at a Low Proton Energy

QGSP BERT: W. Bertini, Phys. Rev. 188, 1711–1730 (1969). "Intranuclear cascade"

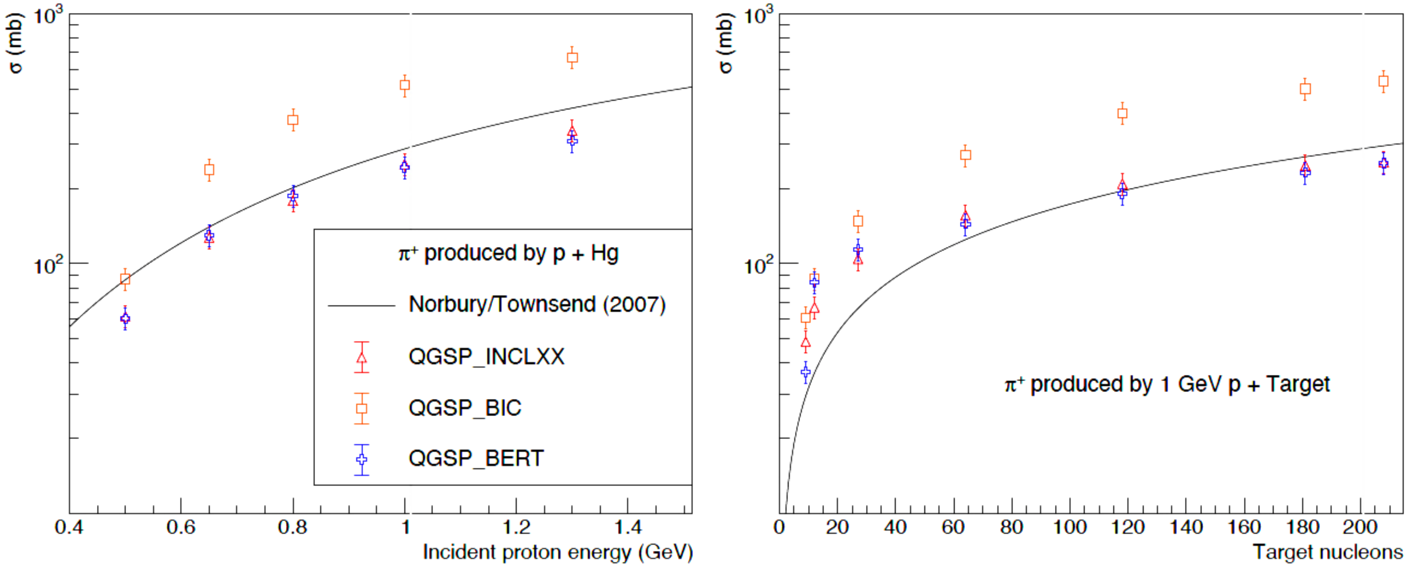
FTFP BERT: At low proton energy gives negligible difference from QGSP BERT

QGSP BIC: G.Folger, V. N. Ivanchenko, and J. P.Wellisch, Eur. Phys. J. A 21, 407–417 (2004). "The binary cascade"

QGSP INCLXX Boudard et al., Phys. Rev. C **87**, 014606 (2013). "Liege intranuclear cascade"

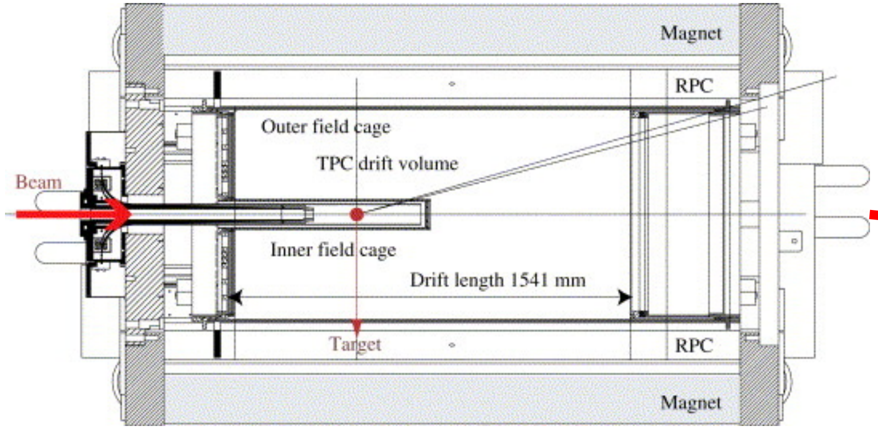
In addition, there is a **Norbury, Townsend** parametrization: W. Norbury and L. W. Townsend, Nucl. Instrum. Meth. B 254, 187–192 (2007).

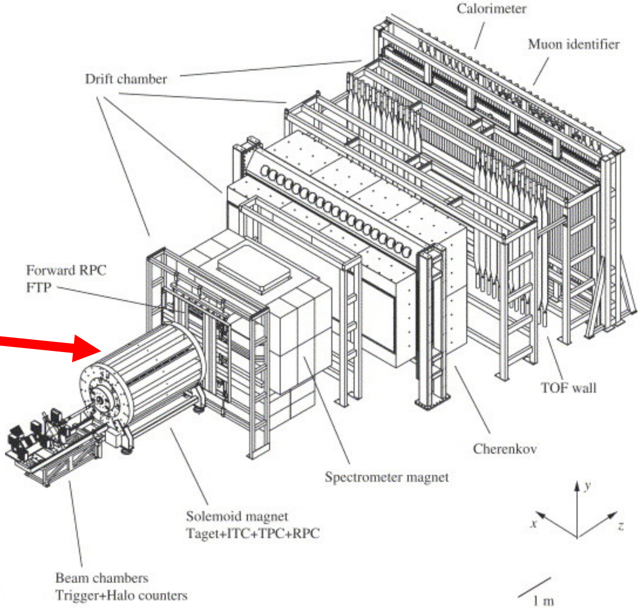
$$\sigma_{\pi^+} = \frac{A_t^{2.2/3}}{0.00717 + 0.0652\frac{log(E_i)}{E_i} + \frac{0.162}{E_i^2}}$$



HARP Experiment at CERN

$20^0 < \theta < 160^0$





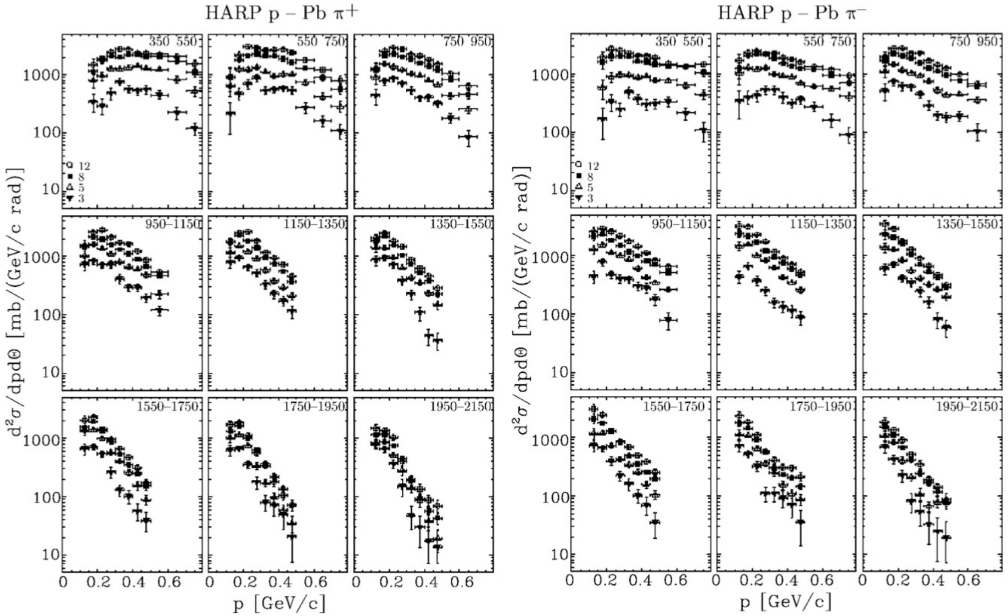
Targets:

H_2, d_2, N_2, O_2, Be, C, Al, Cu, Sn, Ta, Pb

Large-angle production of charged pions by 3–12.9 GeV/c protons on beryllium, aluminium and lead targets

Regulara Article – Experimental Physics | Open access | Published: 12 January 2008

Volume 54, pages 37–60, (2008) Cite this article

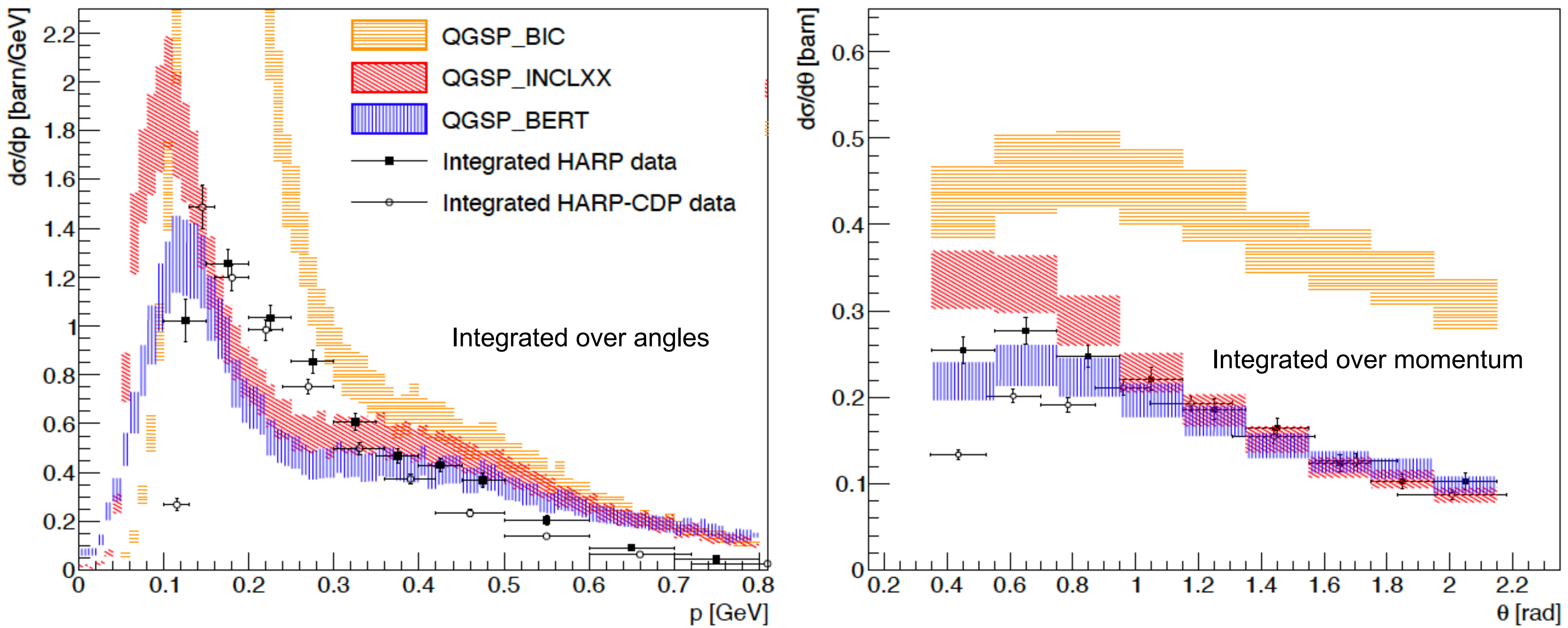


Minimum Proton Energy:
2.2 GeV

Pions Momentum:
0.2 < GeV/c <0.6

Pions Angle:
$20^0 < \theta < 120^0$

HARP p(2.2 GeV) + Pb → π^+ comparison with models.



Two sets of experimental points corresponds to two different analysis of the same data set.

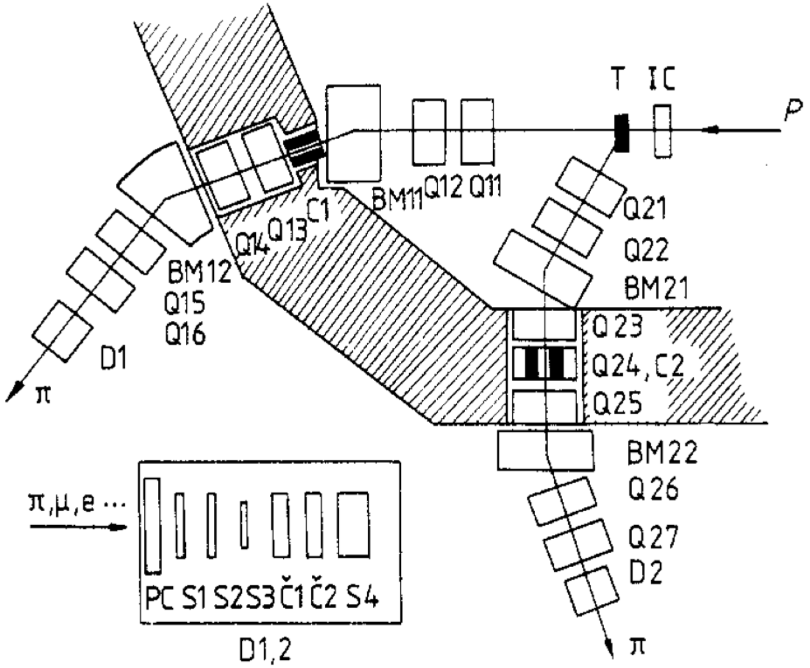
Non of the three GEANT-4 models is perfect

However, BERT looks like having the best agreement with the data

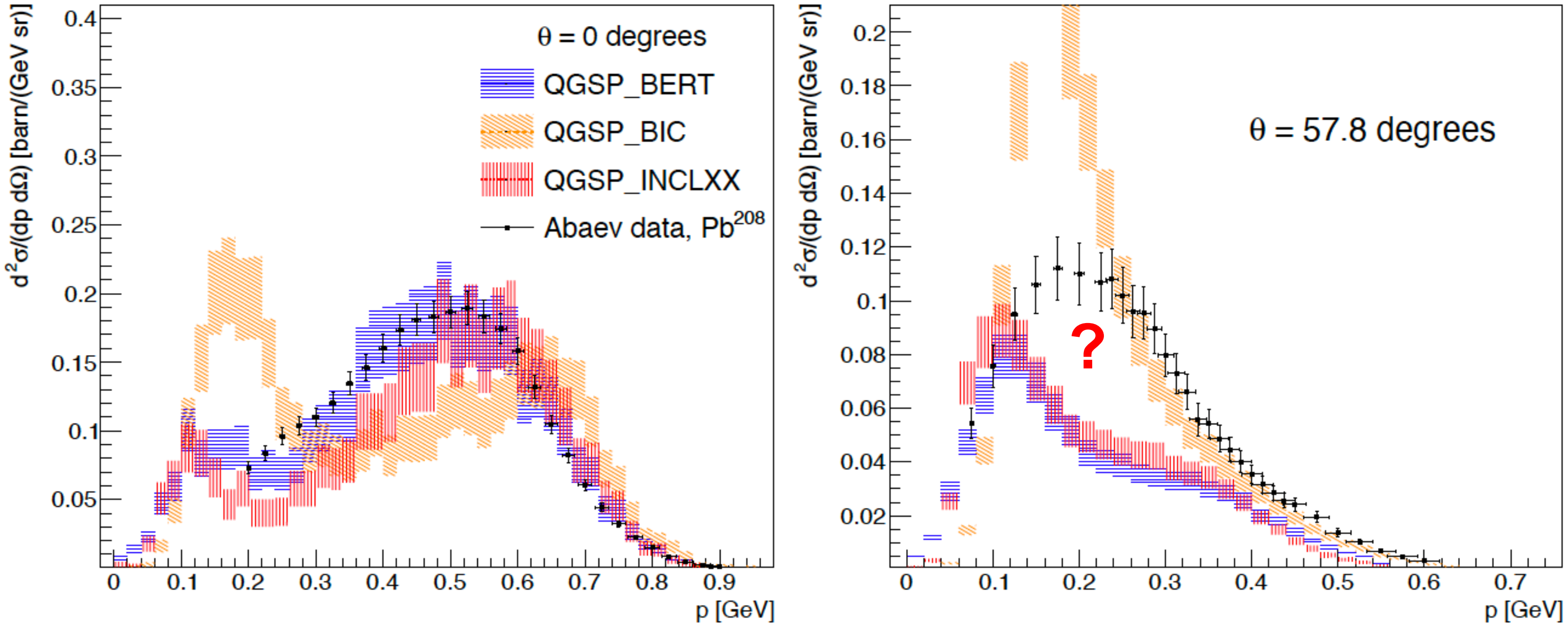
One More Reference Point is from the Gatchina Experiment

Abaev et al., "Inclusive Pion Production at the Angles 0-degrees and 57.8-degrees in 1-GeV Proton Nucleus Collisions", J. Phys. G 14, 903–929 (1988).

Targets were: ^{1}H, ^{2}D, ^{10}B, ^{11}B, ^{12}C, ^{16}O, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{27}A1, ^{64}Cu, ^{116}Sn, ^{124}Sn, ^{181}Ta, ^{184}W and ^{208}Pb



p(1 GeV) + Pb → π^{+}

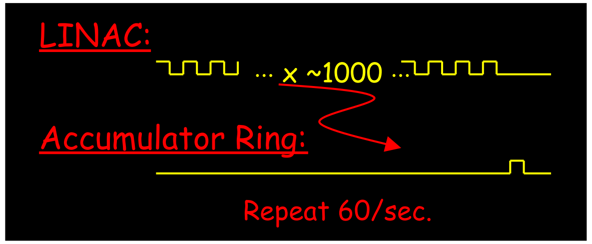


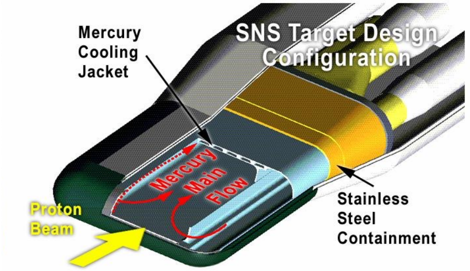
QGSP_BIC is strongly disfavored

Nothing is perfect. For SNS we did use BERT package

COHERENT Experiment is Based at SNS (ORNL)

- *1 GeV, 1.7 MW proton driver*
- It is the world's most powerful pulsed neutrino source. Presently it delivers 9.2 · 10^{20} POT daily *~8% of protons produce 3 neutrino flavors*
- Neutrino energies at SNS are ideal to study CEvNS and low energy neutrino interactions
- *99% of neutrinos have energy < 53 MeV*
- Decay At Rest from pions and muons (DAR) gives very well-defined neutrino spectra
- 60 Hz, ~400 nsec beam spills let suppression of steady background by a factor of 2000.

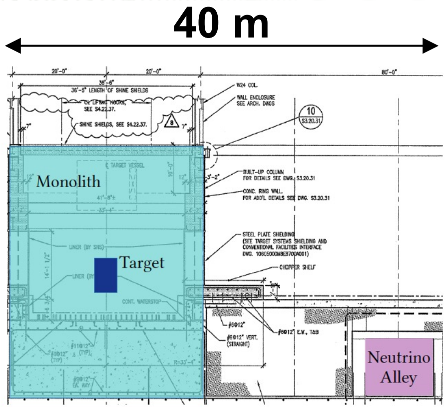




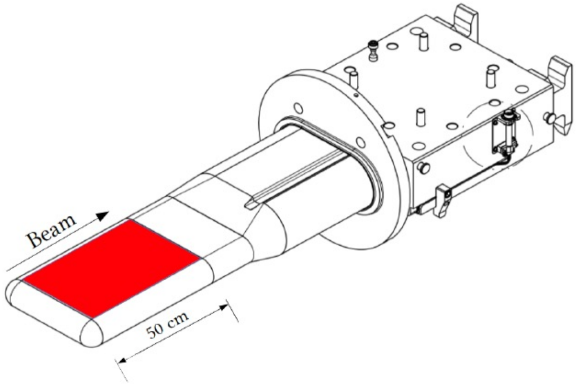
Compact Mercury Target (7 x 40 x 50 cm^3)

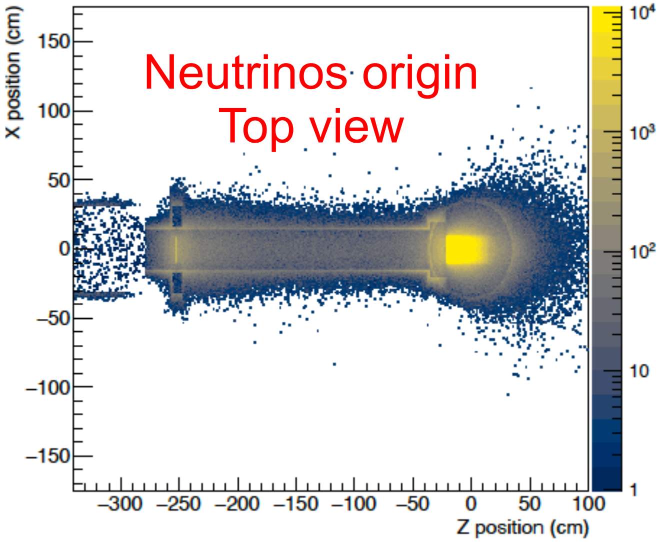
Neutrino Simulations for SNS

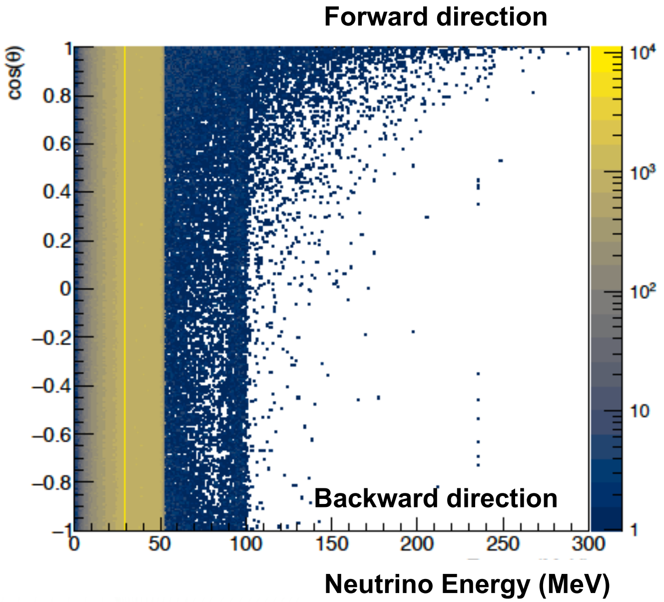
Target Shielding

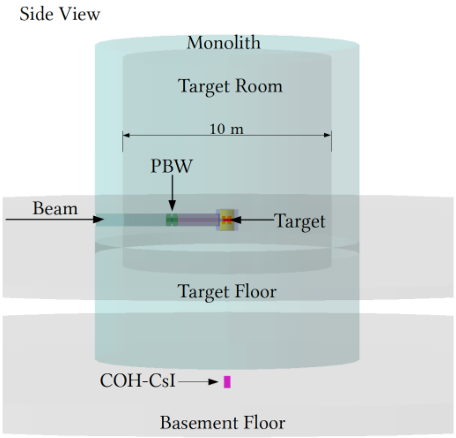


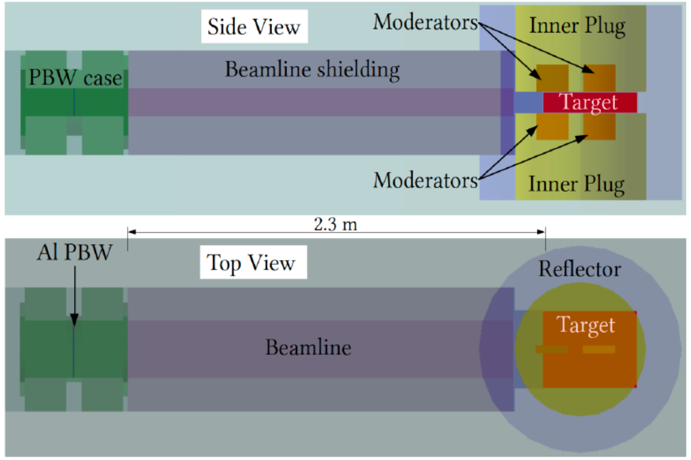
SNS Mercury Target

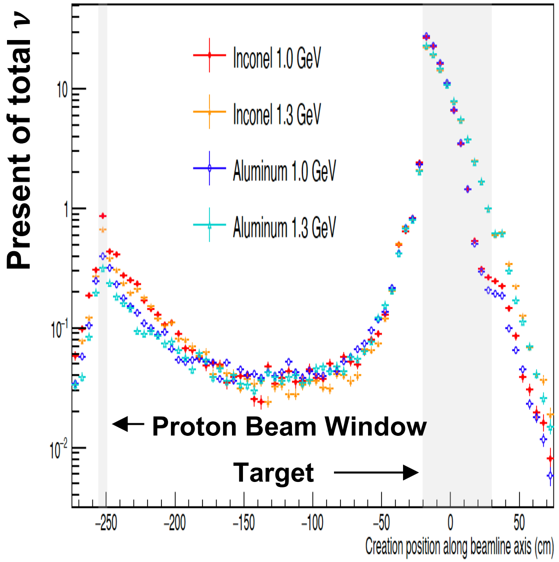






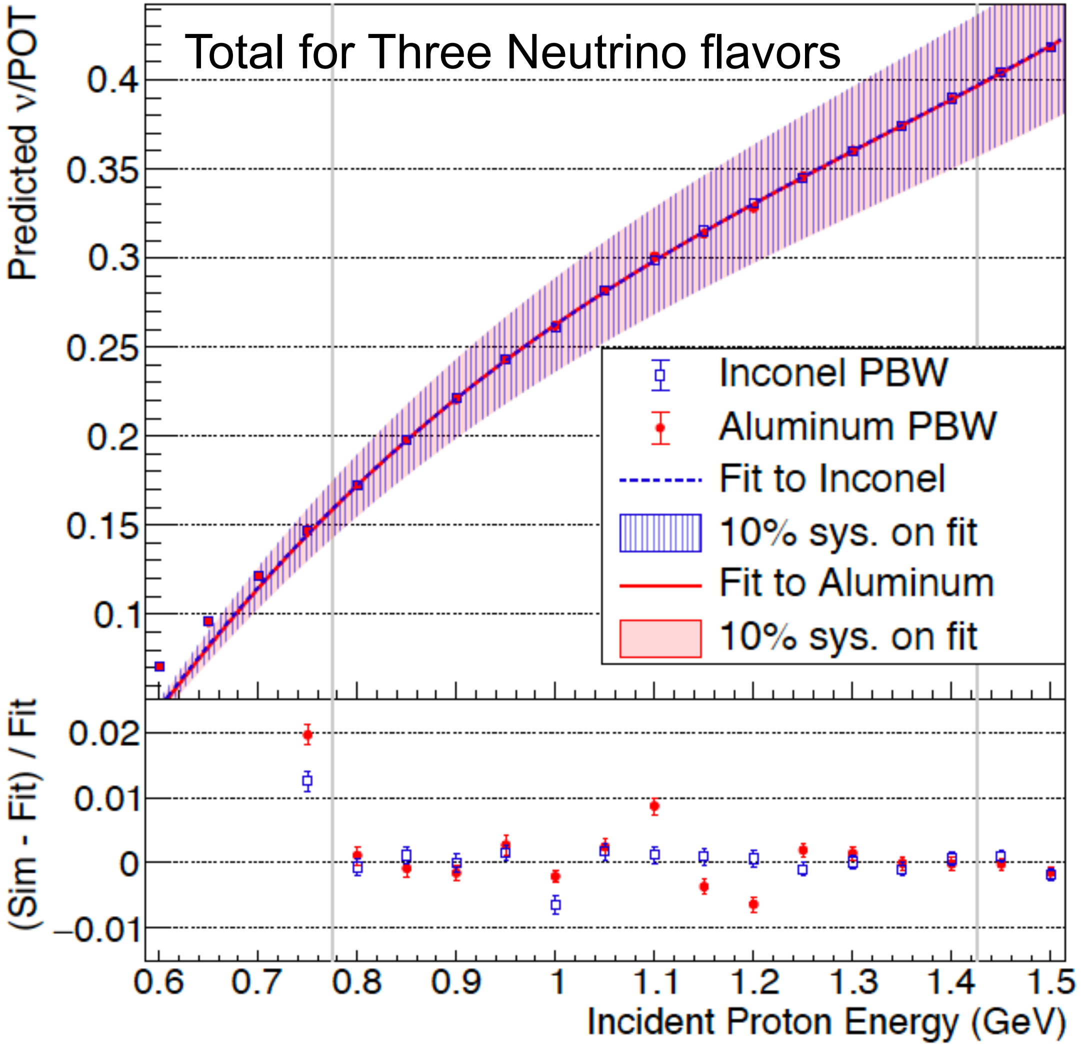


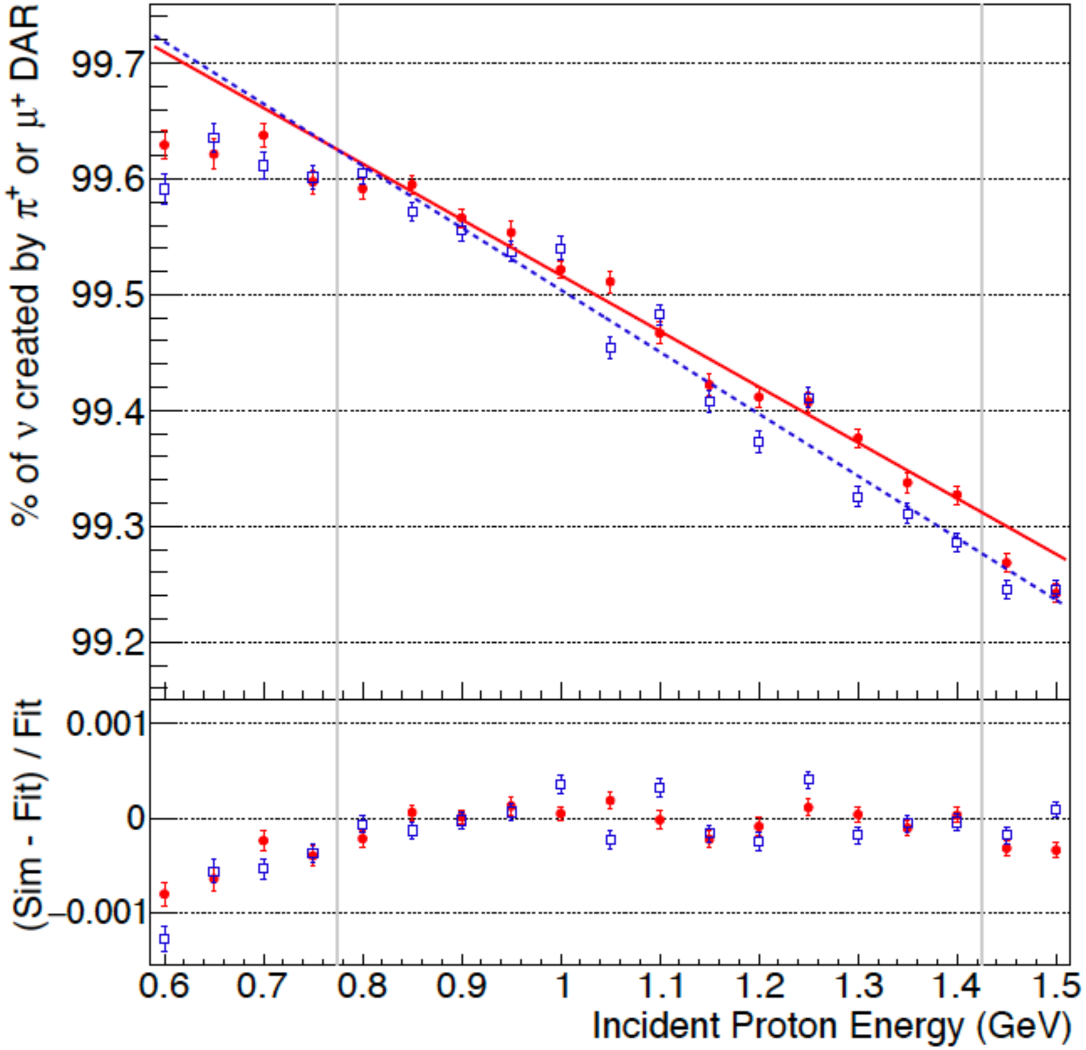




Vast majority of neutrinos are isotopically generated within the target in a compact volume

Neutrino Flux Prediction for the SNS





Parametrization

$$\frac{\nu_i}{p} = 0.28 \cdot E^2 - 1.12 \cdot E + 1.79 - \frac{0.68}{E}$$

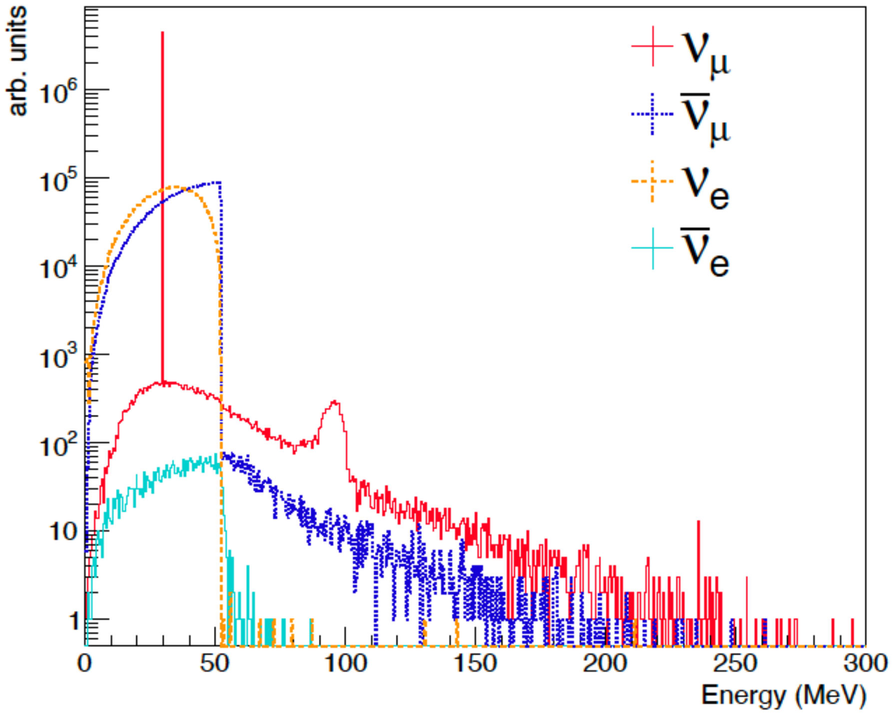
Neutrino Flux from the SNS

After running multiple simulations, we believe that we know neutrino flux with

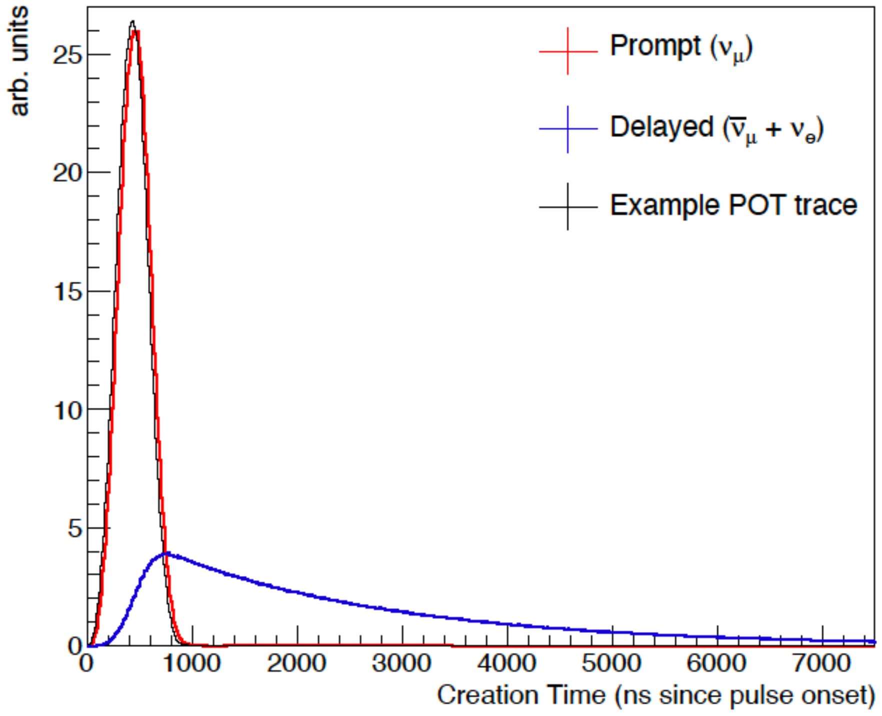
10% accuracy

Neutrino energy and time distribution we know well.

Neutrino Energy



Neutrino Timing



Can we do better for the SNS flux normalization?

OAK RIDGE National Laboratory

Concept of Heavy Water Detector to Measure Neutrino Flux

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Prompt NC ν_{μ} +d → 1.8×10^{-41} cm²
Delayed NC $\nu_{e\mu\text{-bar}}$+ d →6.0×10^{-41} cm²
Delayed CC ν_{e} + d → 5.5×10^{-41} cm²

For ~1 t fiducial mass detector ~ thousand interactions per year

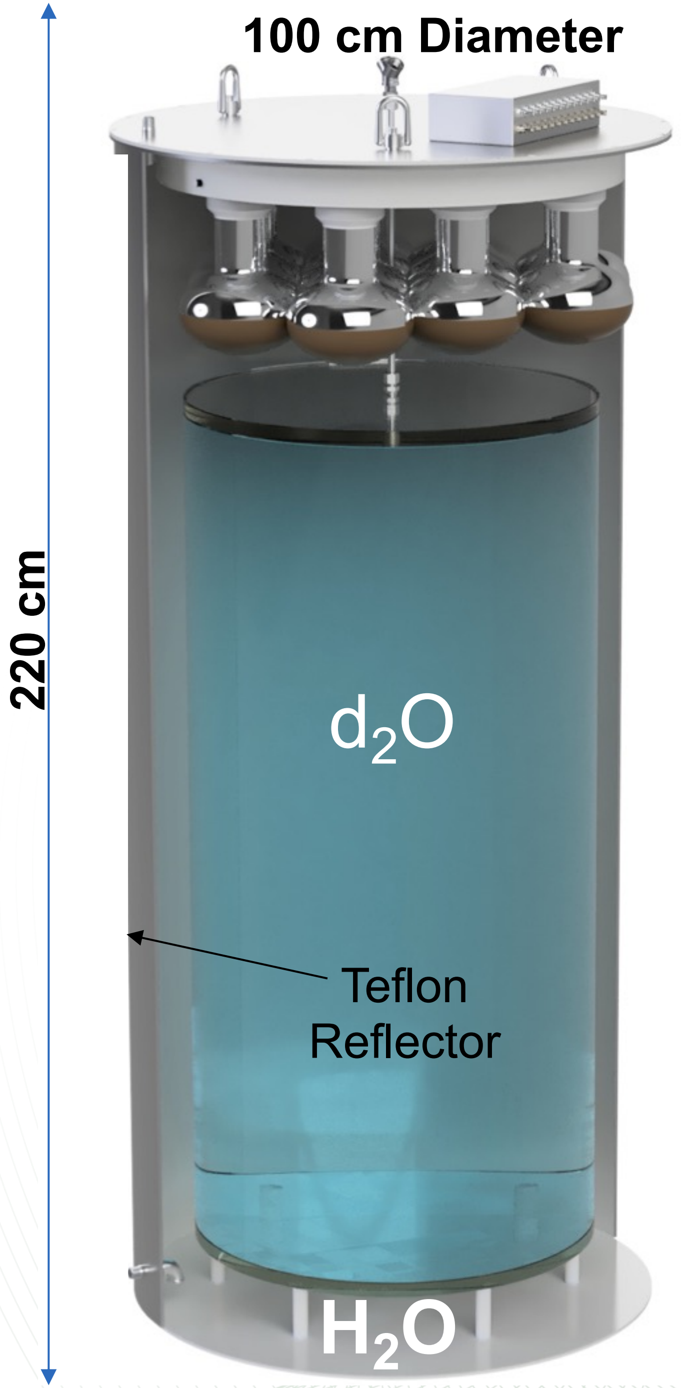
Detector calibration with Michel Electrons from cosmic muons (same energy range)

- Neutrino Alley space constraints for the D2O detector: 1 m depth x 2.3 m height
- Locations 20 meters from target

Will do CC measurement on Oxygen for SN support

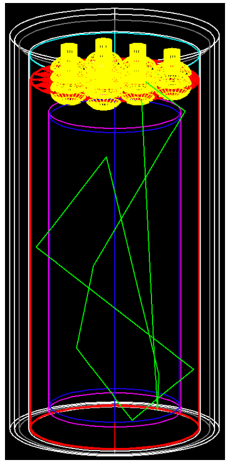
Specifications

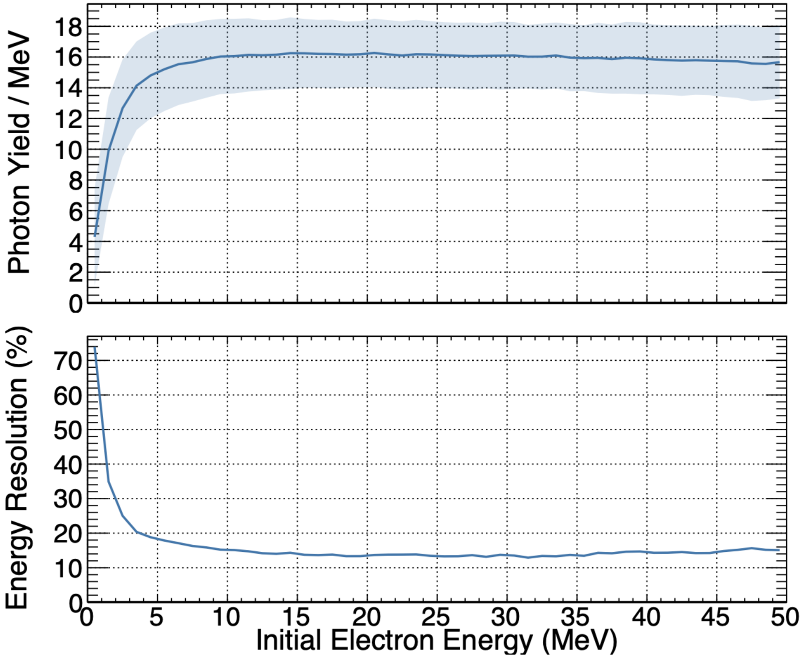
- 0.6 tons D_2O within acrylic inner vessel
- Water Cherenkov Calorimetry
- 10 cm H_2O "tail catcher" for high energy e^-
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel
- Lead Shielding
- Hermetic veto system

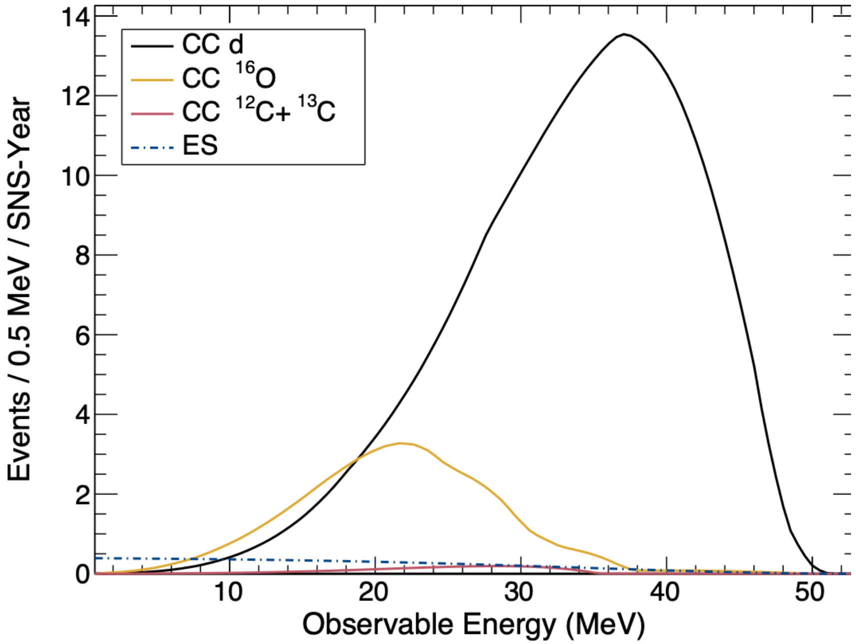


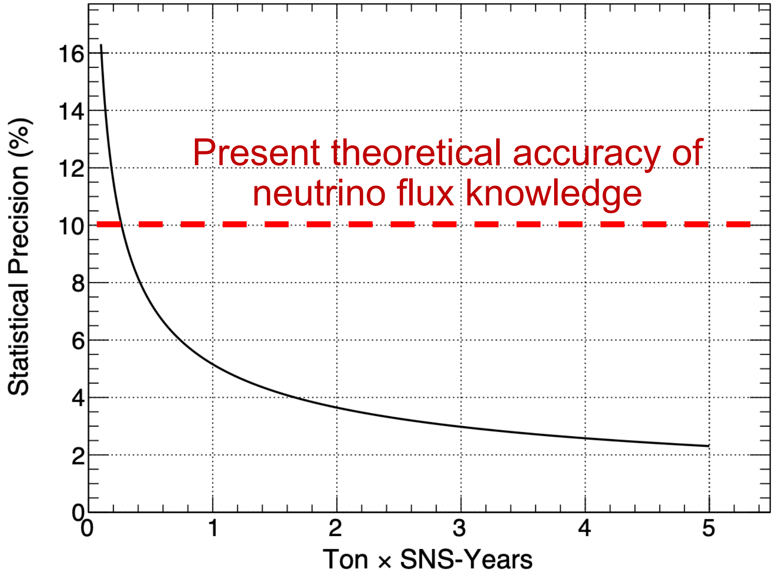
Predictions for d_2O Detector Response

See JINST 16 (2021) 08, P08048







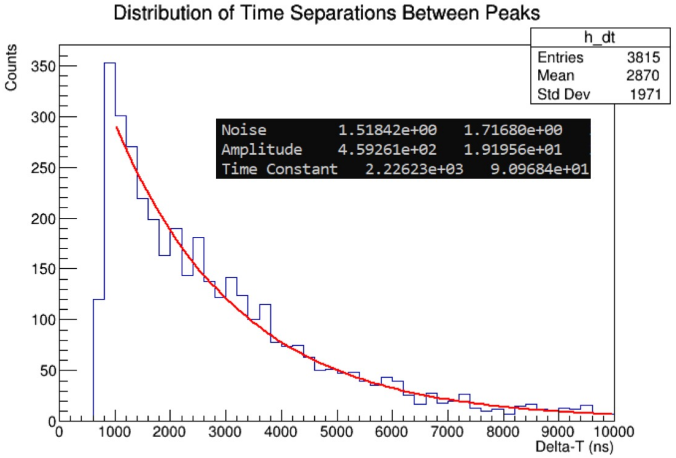


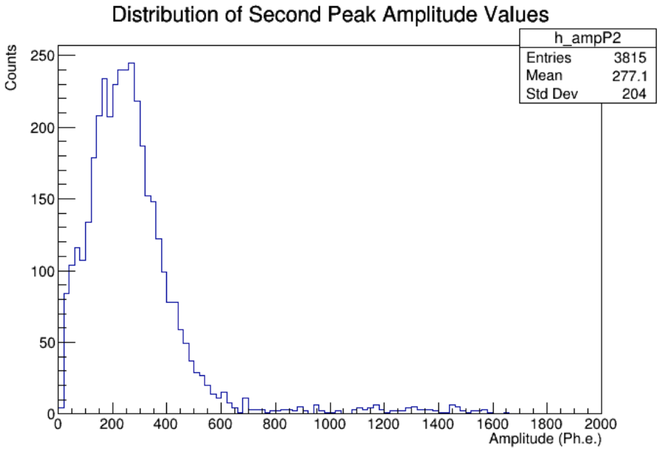
Detector has been deployed last summer

Detector Deployment

We will have two Identical modules.
Second with H2O only. (Under Construction)

Detector energy calibration via Michele electrons





d_2O detector started to accumulate statistic last summer.

We logged only one month of SNS running before accelerator shutdown.

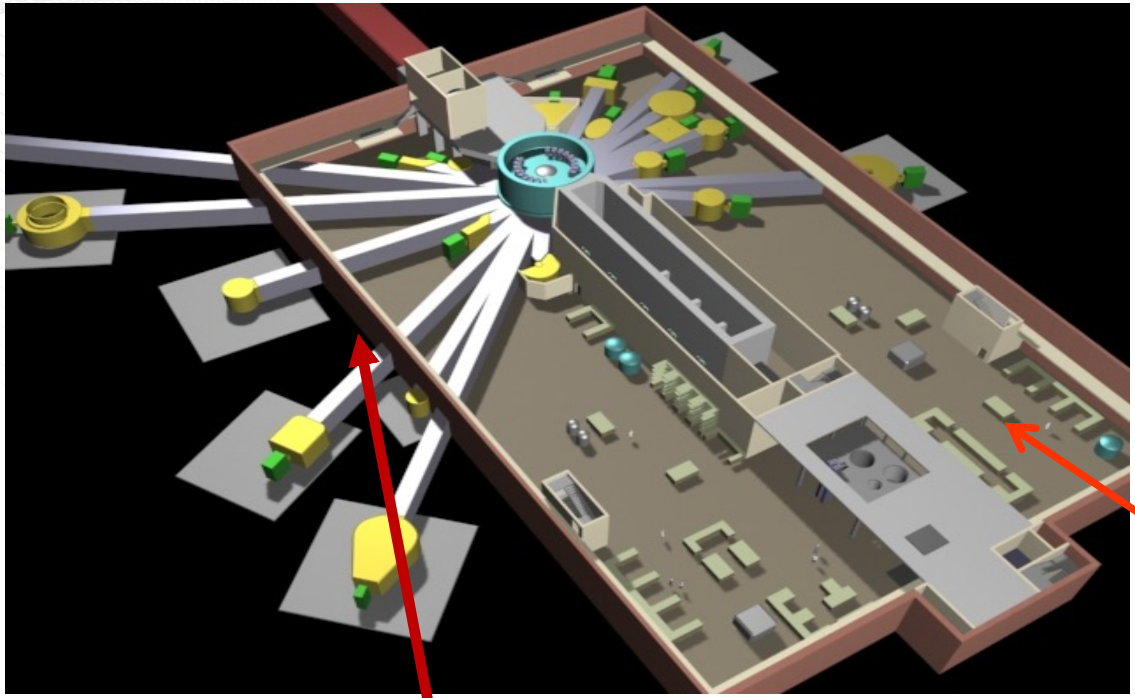
We recorded 1GWh or $2.25 \cdot 10^{22}$ POT

With two detectors we expect to have
~3 νd and ~3 νO interactions per day.

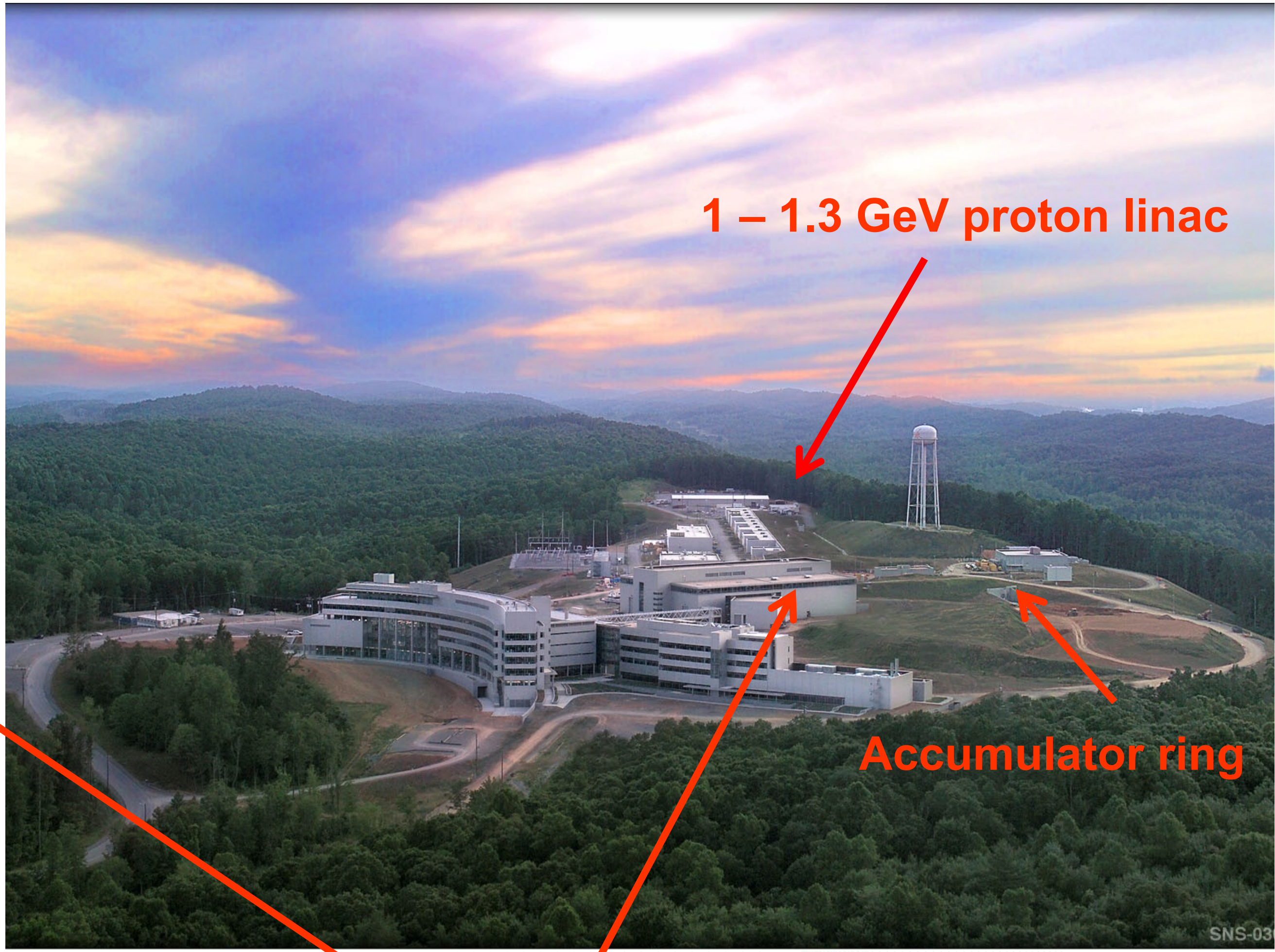
OAK RIDGE National Laboratory

Neutrino Alley

After extensive BG studies, we find a well protected location



We have 1m · 2m · 25m of a good space !!!

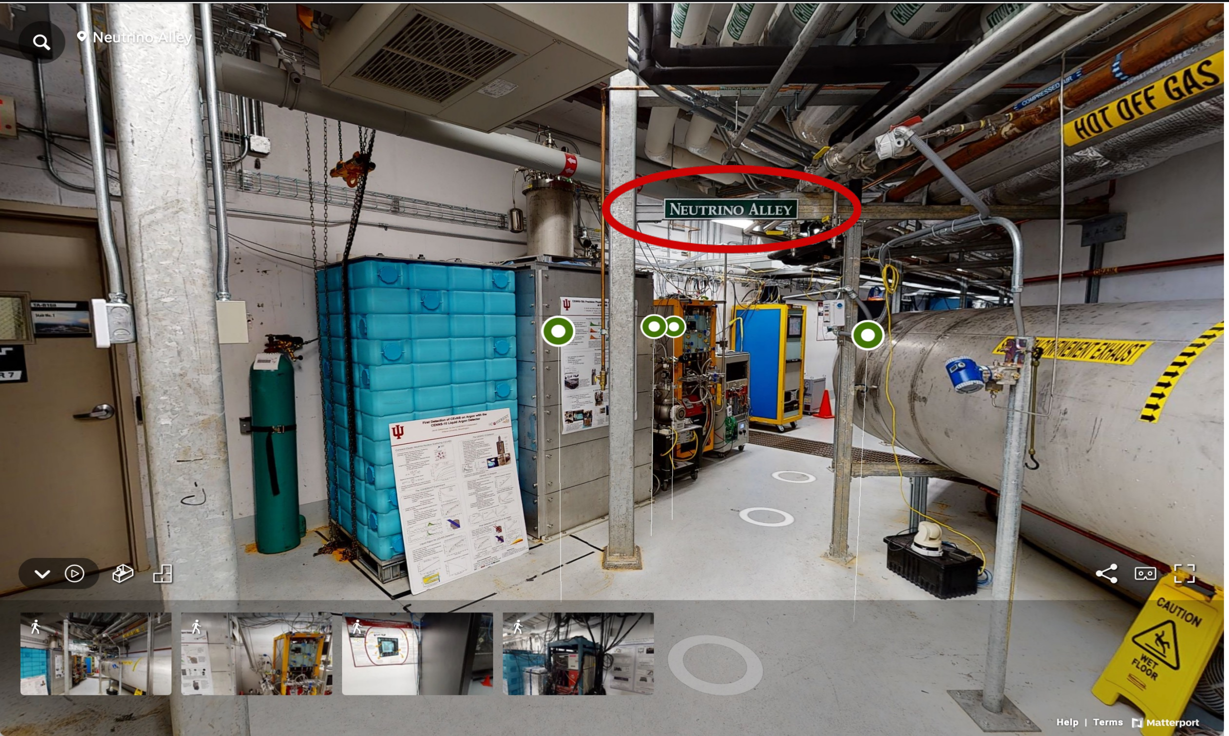


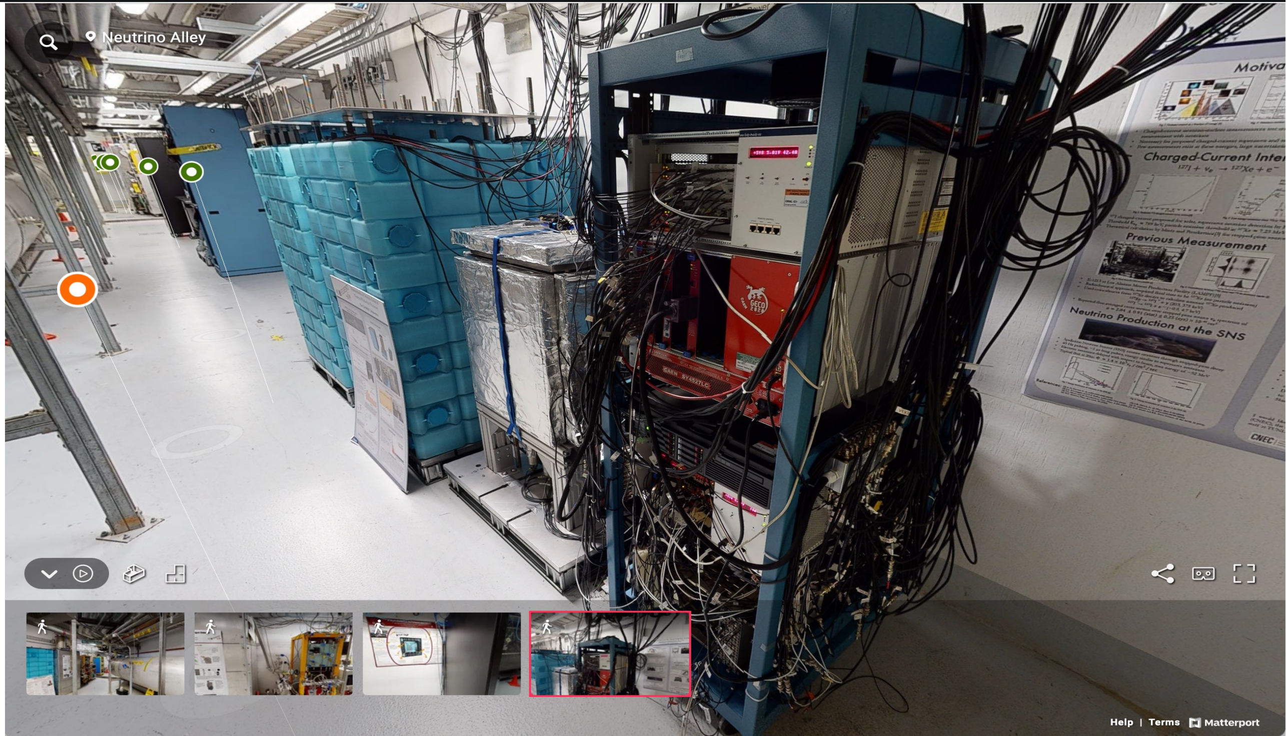
Target Building

It is 20-30 meters from the target. Space between the target and the alley is filled with steel, gravel and concrete

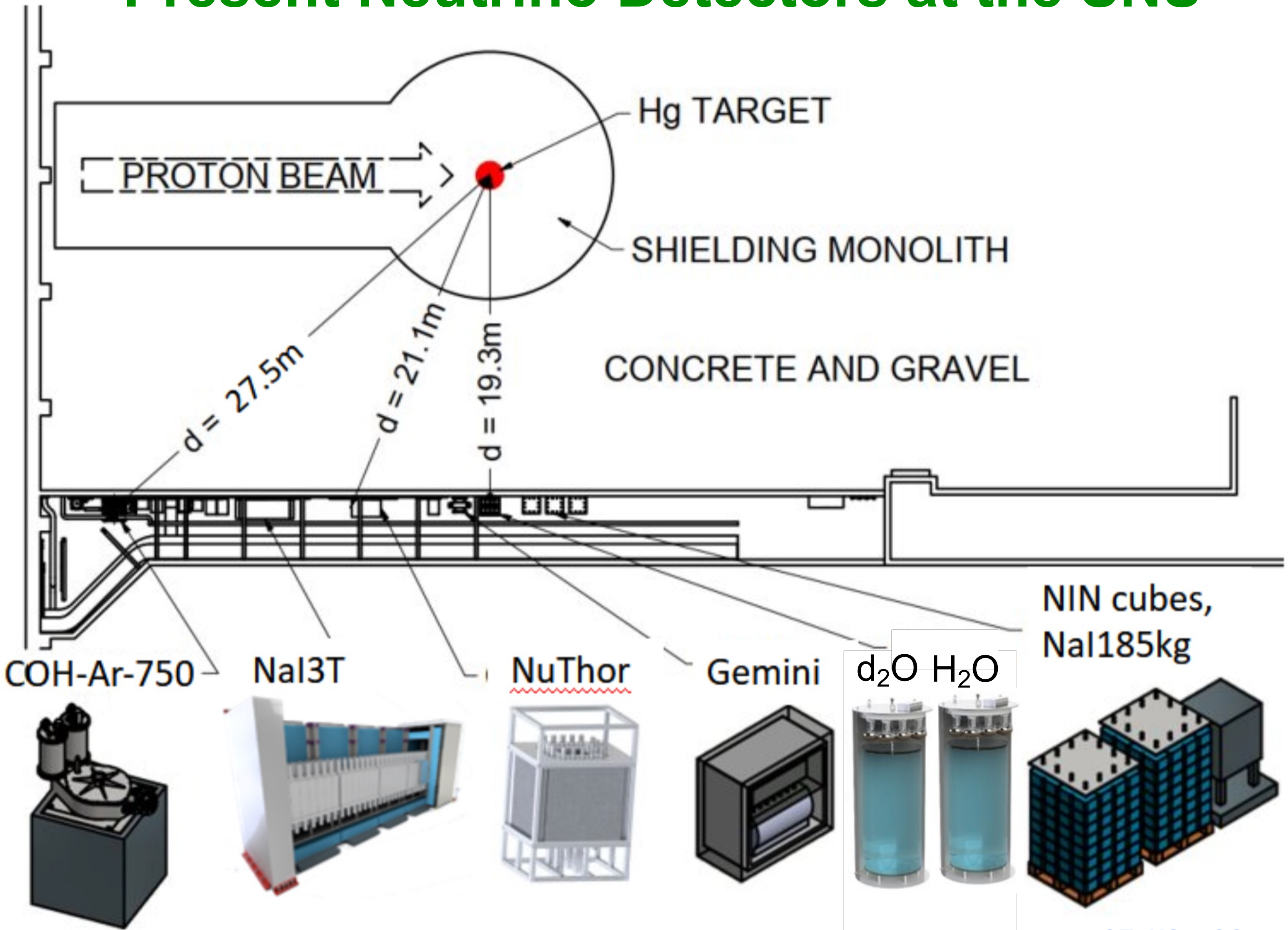
There are 10 M.W.E. from above

Study of CEvNS is the major inspiration for the neutrino physics program at the SNS (Rex Tayloe talk on Wednesday)





Present Neutrino Detectors at the SNS



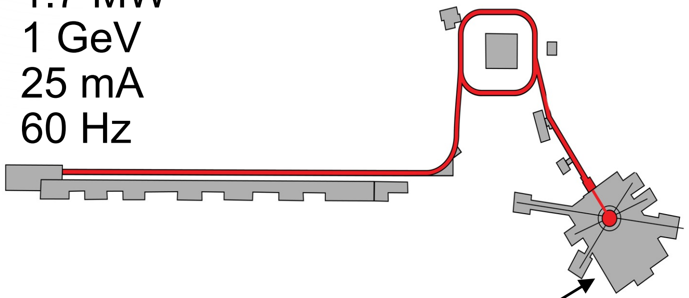
CEvNS + CC on Ar	CEvNS + CC on Na, I	ν fission on Th	CEvNS + CC on Ge	Flux + CC on O	CEvNS + CC on Na, I

PPU and STS upgrades for SNS are coming

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.7 MW
1 GeV
25 mA
60 Hz

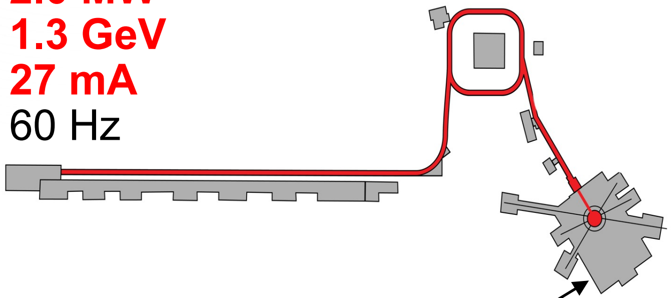


FTS
1.7 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



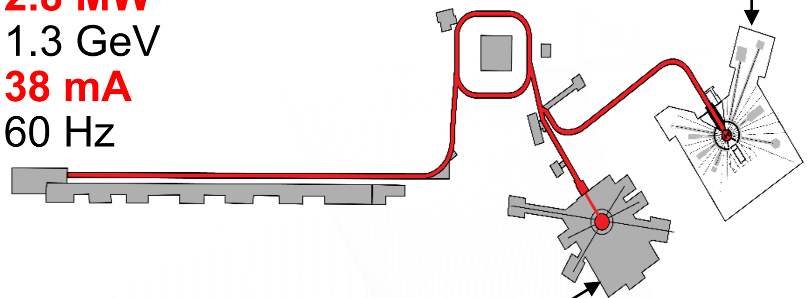
FTS
2 MW
60 Hz

2028 after STS

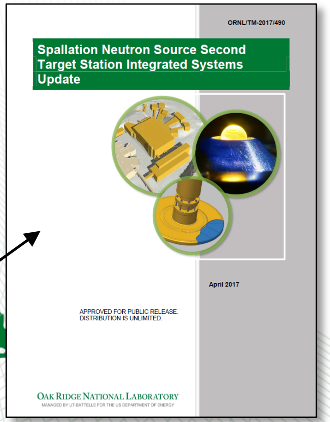
- **2000+** users
- Hierarchical materials, time-resolution and small samples

STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec



The choice of 15 Hz and 0.7 MW resulted from a detailed analysis of STS design (reviewed by a panel of experts in 2017) and optimizes performance of STS without impacting performance of FTS

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Summary

COHERENT SNS SPALLATION NEUTRON SOURCE

There are challenges to calculate DAR neutrino flux for spallation targets

We found that the BERT model is probably closest to reality but has some limitations

We are open to any other suggestions

We will normalize neutrino flux at the SNS experimentally to a 2% accuracy with d_2O detector

Gained knowledge will be beneficial for the other spallation facilities

With flux measurement we will unlock opportunity to test SM with a high accuracy

Most of the simulation used here were performed by:
Dr. R. Rapp, former Ph.D. student at the CMU.

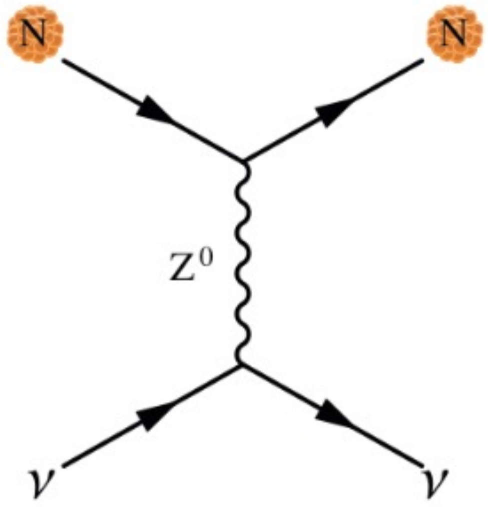
OAK RIDGE National Laboratory

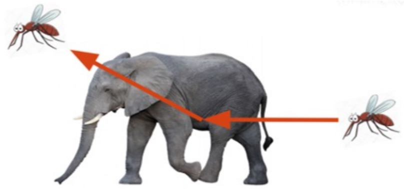
Backups

Coherent Elastic neutrino-Nucleus Scattering

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole, produce tiny recoils.

$$\sigma = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z(1-4\sin^2\theta_W) - N\right]^2 F^2(Q^2) \quad \propto N^2$$

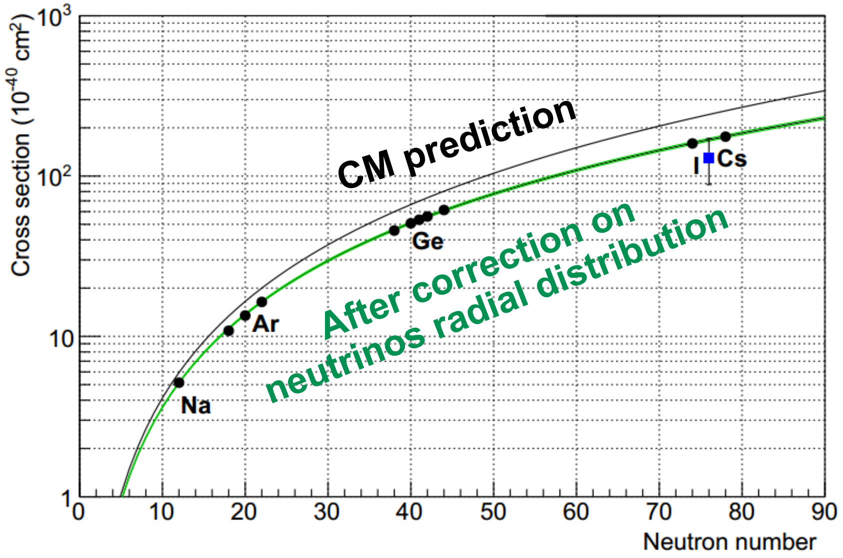


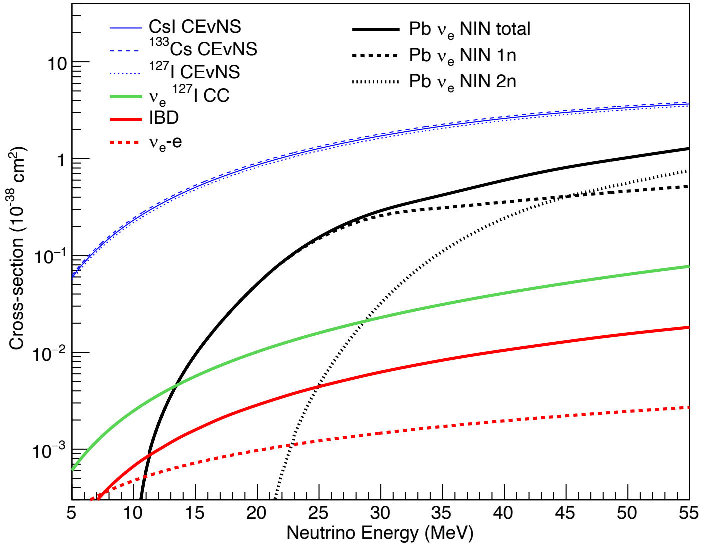


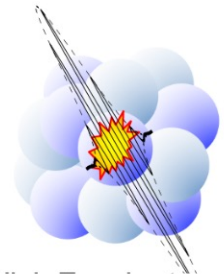
CEvNS cross-section is large, but very hard to detect

D.Z. Freedman PRD 9 (1974)

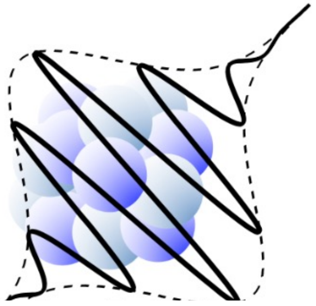
> Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.





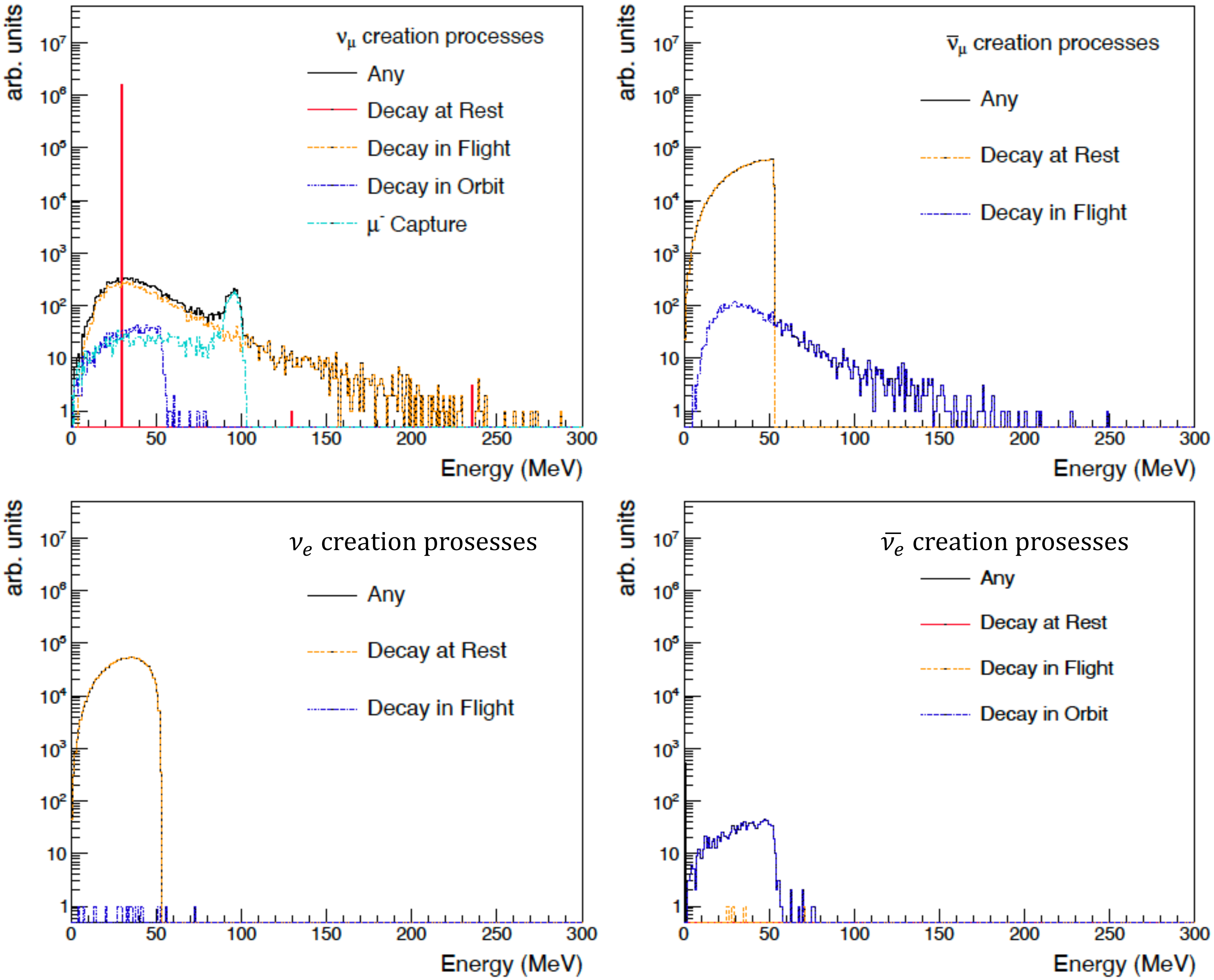


High Q = short de Broglie wavelength



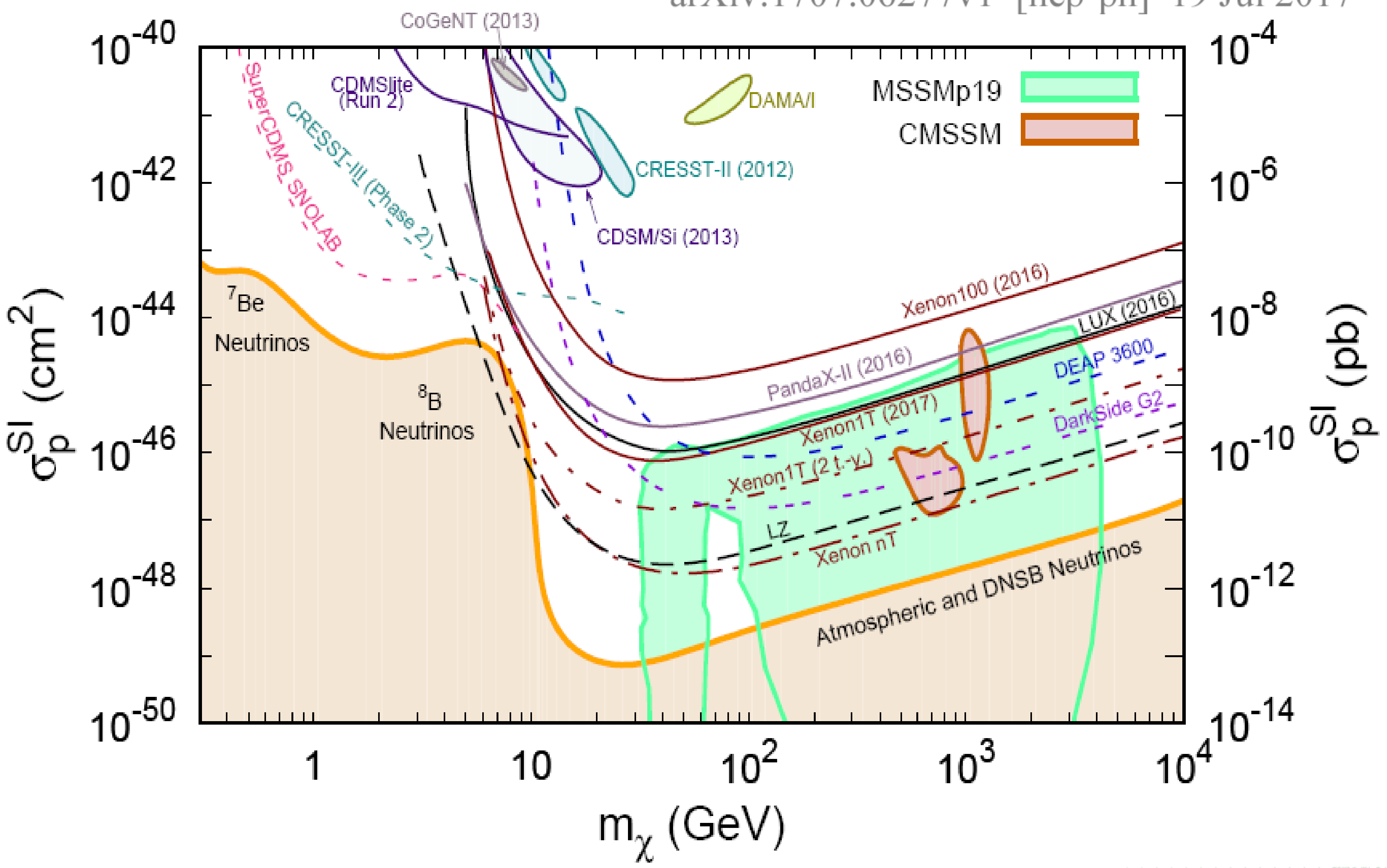
Low Q = long de Broglie wavelength

Antineutrino flipped



CEvNS is Neutrino Floor for DM Experiment

arXiv:1707.06277v1 [hep-ph] 19 Jul 2017



CEvNS is a Probe of Non-Standard Neutrino Interactions (NSI)

new interaction specific to ν's

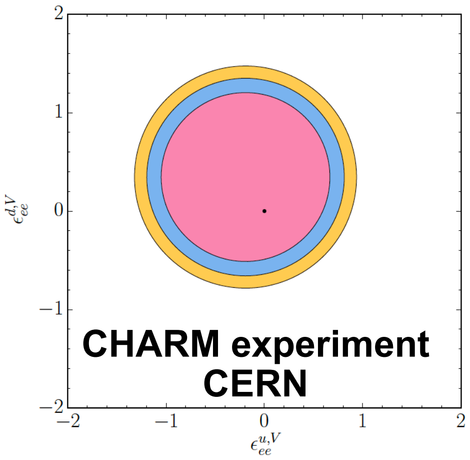
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

J. H J. High Energy Phys. 03(2003) 011

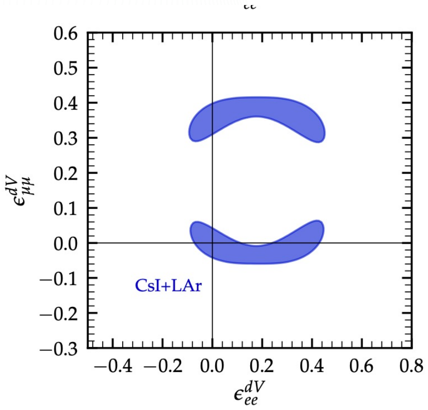
TABLE I. Constraints on NSI parameters, from Ref. [35].

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Non-Standard ν Interactions (Supersymmetry, neutrino mass models) can impact the cross-section differently for different nuclei



arXiv:2211..11905v1 [hep=ph]



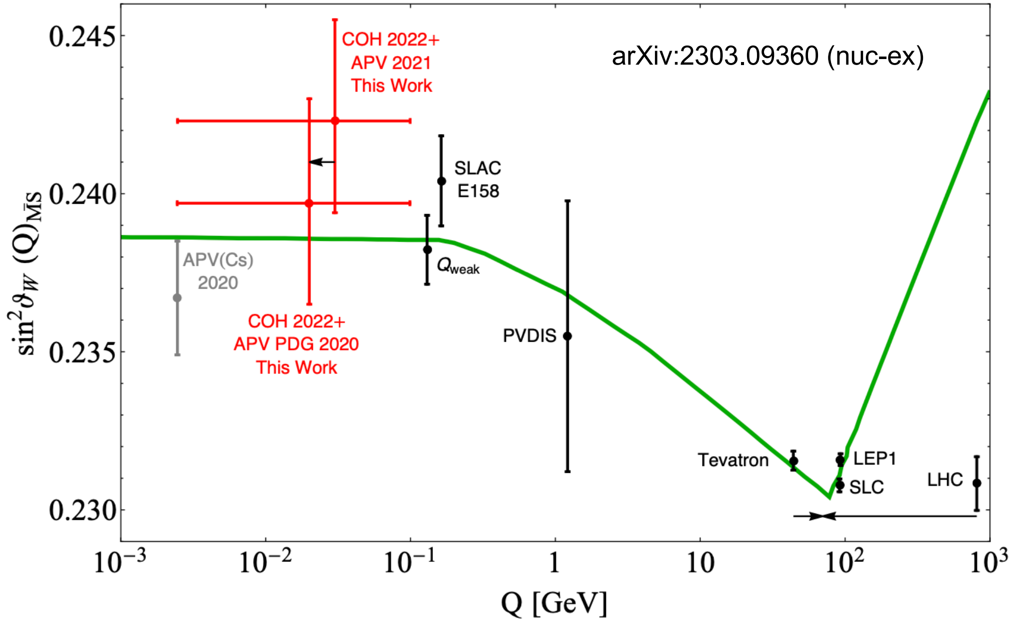
CeVNS is a new way to measure Electro-Week angle at Low Q

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

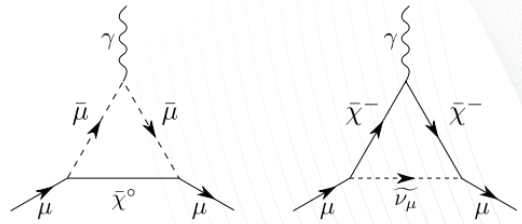
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

Measurements with targets having different Z/N ratio are required.

Sun$^2\theta_w$ is a free parameter in the Standard Model
There is no fundamental theory which explain its value
It is "running" constant, and its value depends on the momentum transfer.



Proposed correction to g-2 for muon magnetic moment due to a light mediator



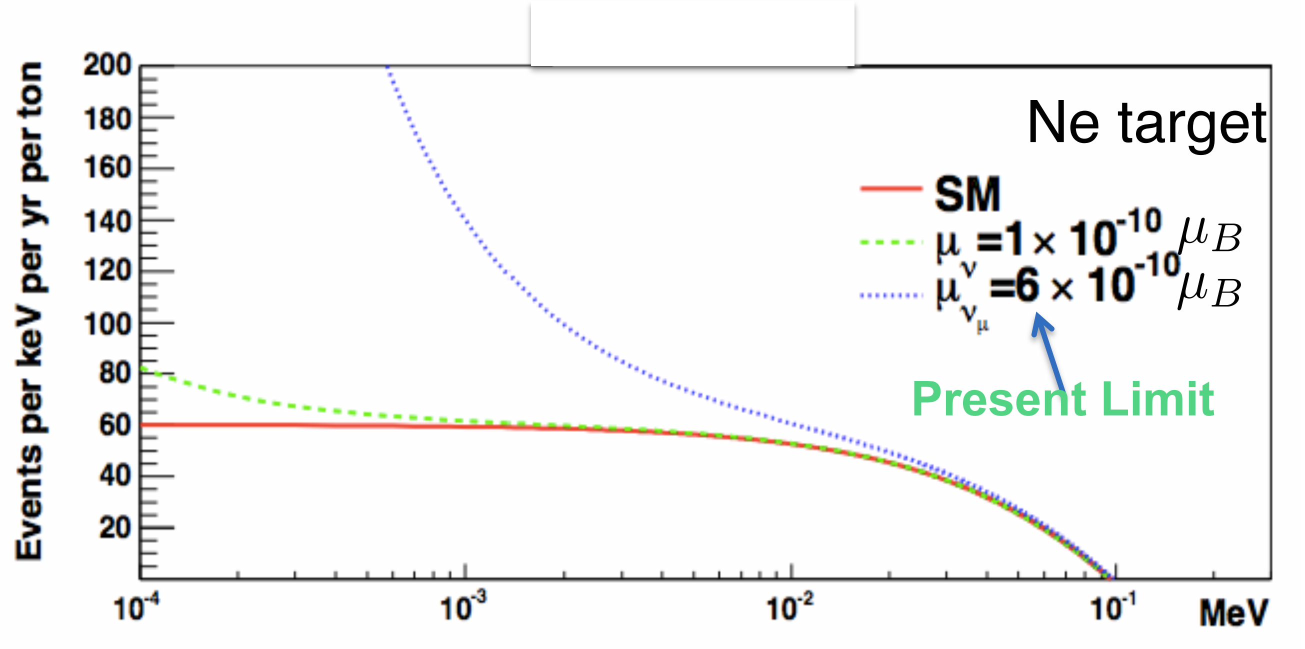
If this is correct it can manifest itself in θ_w value at low Q^2

OAK RIDGE National Laboratory

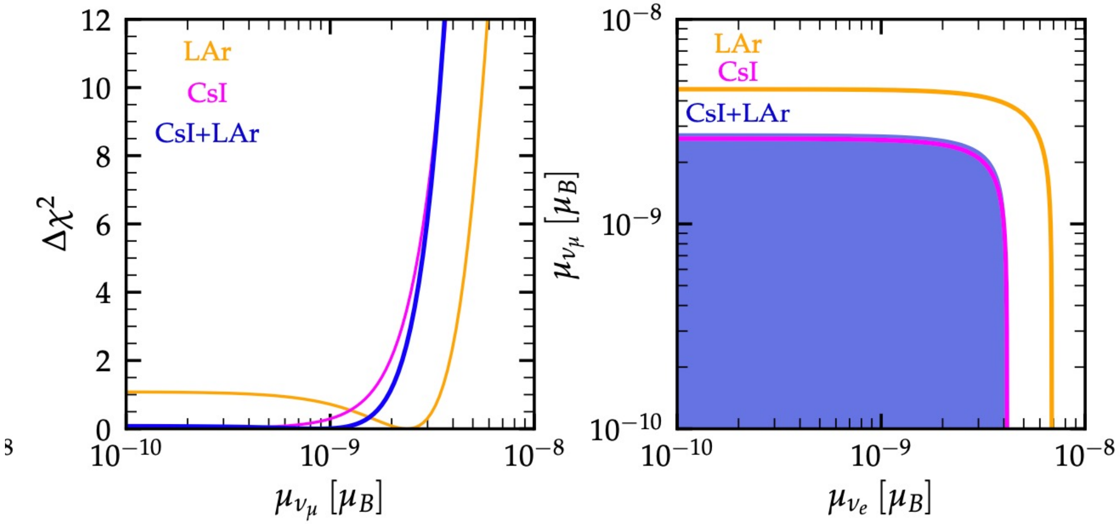
Search For Neutrino Magnetic Moment via CEvNS

Signature is distortion at low recoil energy E

$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-E/k}{E} + \frac{E}{4k^2}\right)$$



arXiv:2211..11905v1 [hep=ph]



See also Kosmas et al., arXiv:1505.03202

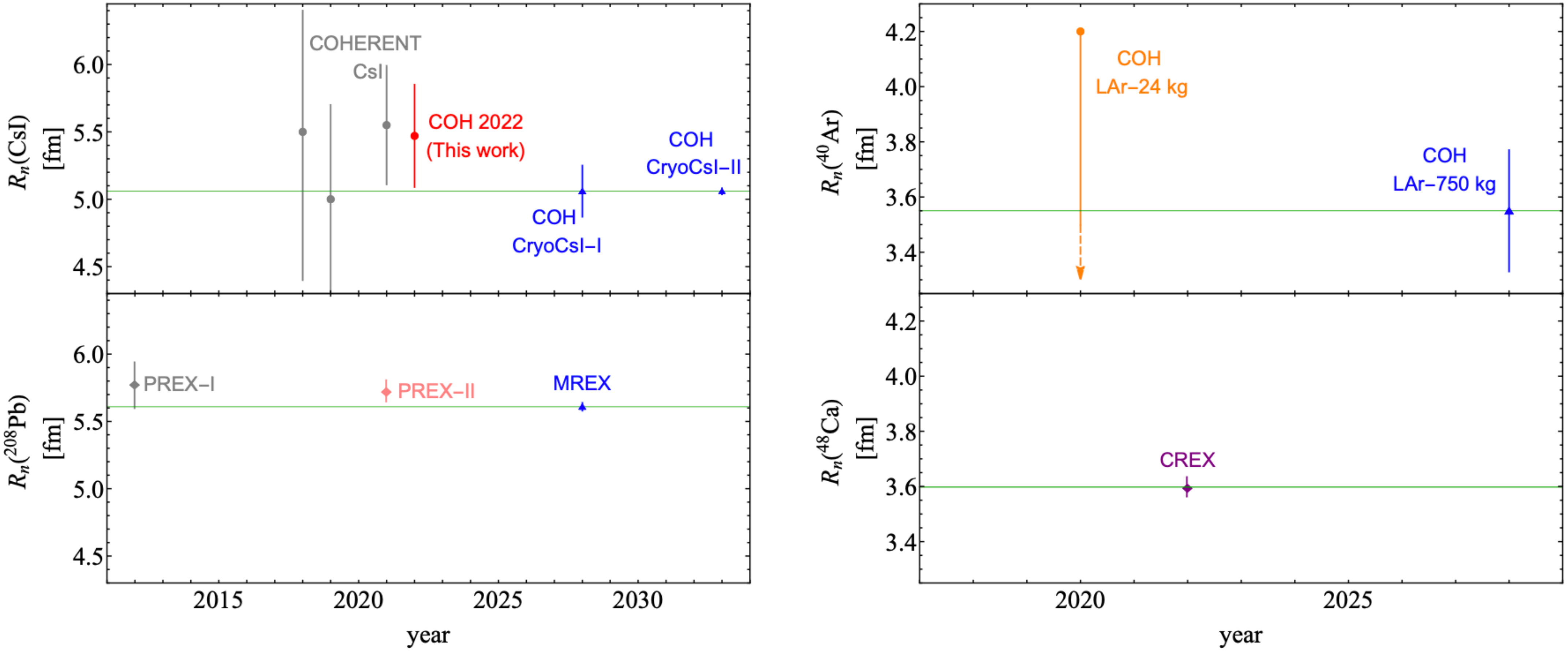
Nuclear neutron radius

arXiv:2303.09360 (nucl-ex)

[Submitted on 16 Mar 2023]

Nuclear neutron radius and weak mixing angle measurements from latest COHERENT CsI and atomic parity violation Cs data

M. Atzori Corona, M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, G. Masia



CEvNS important for Understanding of Supernova Dynamics

Large effect from CEvNS on Supernovae dynamics.
We should measure it to validate the models

J.R. Wilson, PRL 32 (74) 849